NOAA • NESDIS JPSS Joint Polar Satellite System

Understanding Emissions and Tropospheric Chemistry using NUCAPS and VIIRS

A JPSS Proving Ground/Risk Reduction Project

NOAA OAR ESRL: ***G. Frost***, *S. McKeen, R. Ahmadov, S.-W. Kim, M. Trainer, Y. Cui, W. Angevine, B. McDonald, T. Ryerson, J. Peischl, J. Roberts, J. Gilman, J. deGouw, C. Warneke, C. Granier, K. Rosenlof, J. Brioude*

STC: *C. Barnet, A. Gambacorta*

NOAA NESDIS STAR: *R. B. Pierce*

U Wisconsin CIMSS: *N. Smith*

NOAA NESDIS NCEI OGSSD: *C. Elvidge*

Today's talk

- Our PGRR project overview
- Understanding CH_4 and CO sources
- Drivers and methods of NOAA ESRL research
- ESRL studies in oil and natural gas basins
- Preliminary NUCAPS CH_4 analysis - CONUS
- Southern California natural gas leak
- Preliminary NUCAPS CH_4 analysis - Western US
- Future work and milestones

JPSS PGRR Project Overview

Goal: Use aircraft data & atmospheric modeling to characterize NUCAPS CH_4 and CO retrievals and provide constraints on tropospheric CH_4 and CO

Objectives:

- Validate atmospheric chemical-transport models with aircraft and other observations collected during NOAA field campaigns
- Simulate spatial distributions and temporal variability of CH_4 and CO using observationally validated models
- Evaluate NUCAPS CH_4 and CO retrievals with validated model output
- Assess ability of JPSS datasets to constrain modeled emissions, transport and chemistry of CH_4 and CO

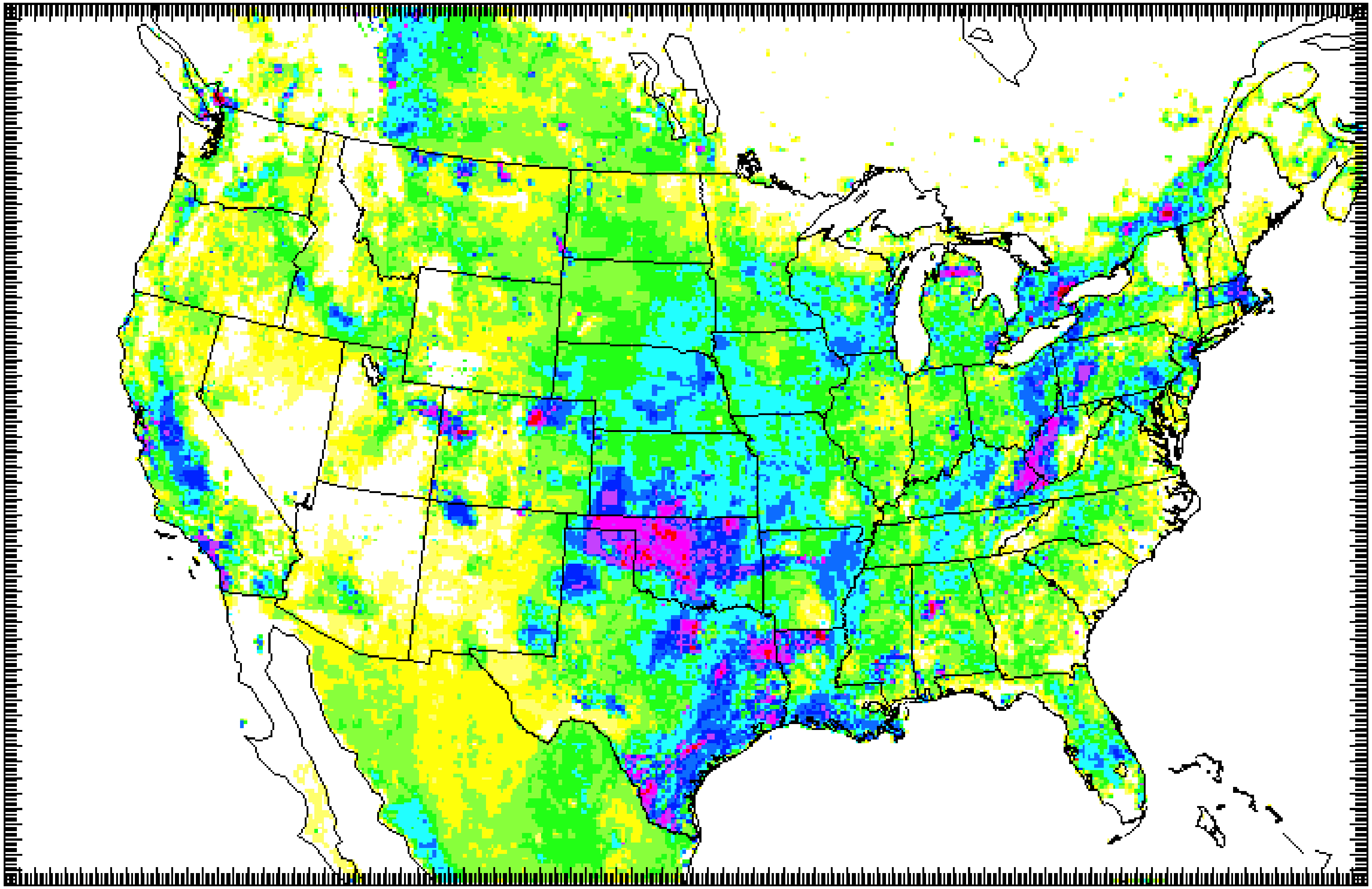
End Users:

- Atmospheric researchers at NOAA, other Fed agencies, academia
- NOAA air quality forecasting

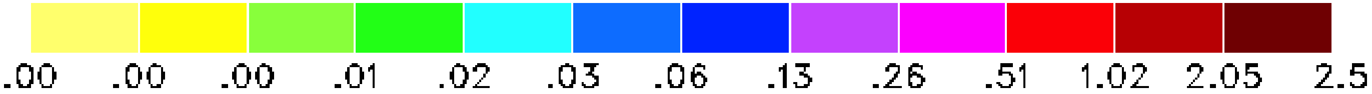
Key Collaborators:

- Close collaboration with NUCAPS retrieval team (Barnet, Gambacorta) and STAR/CIMSS NUCAPS analysis team (Pierce, Smith) is absolutely critical to this project and adds value to PGRR investment

US CH_4 Emissions



CH_4 emissions, kmol km^{-2} hr^{-1}



US CH_4 Emissions are Uncertain

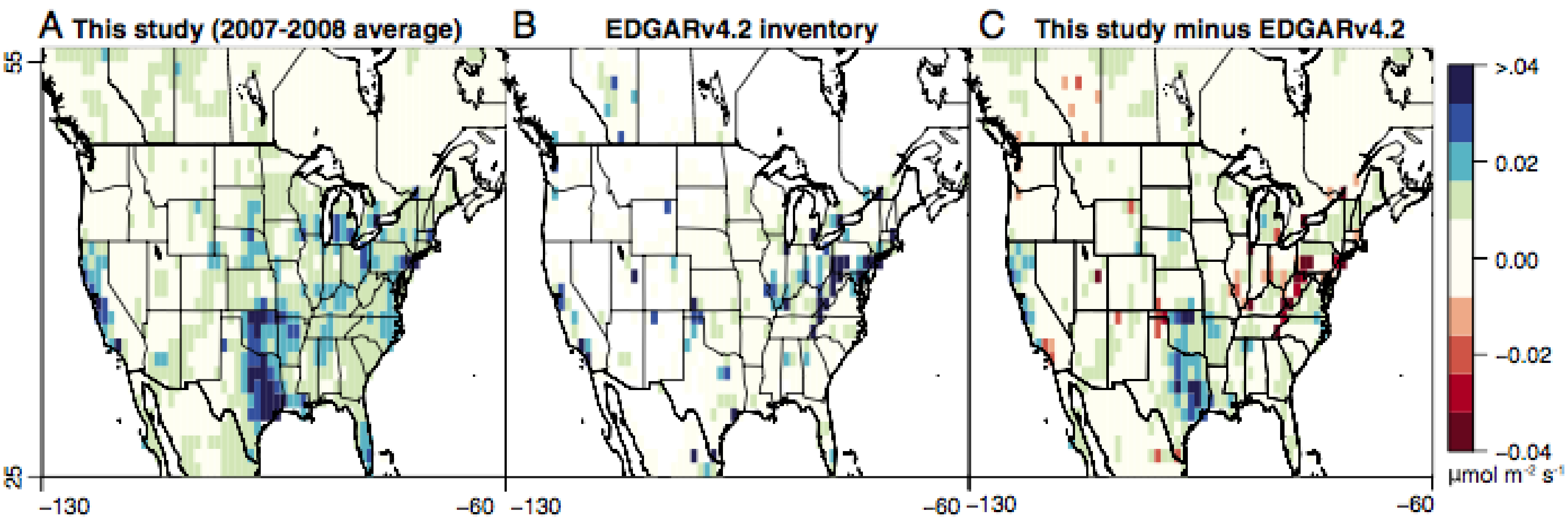
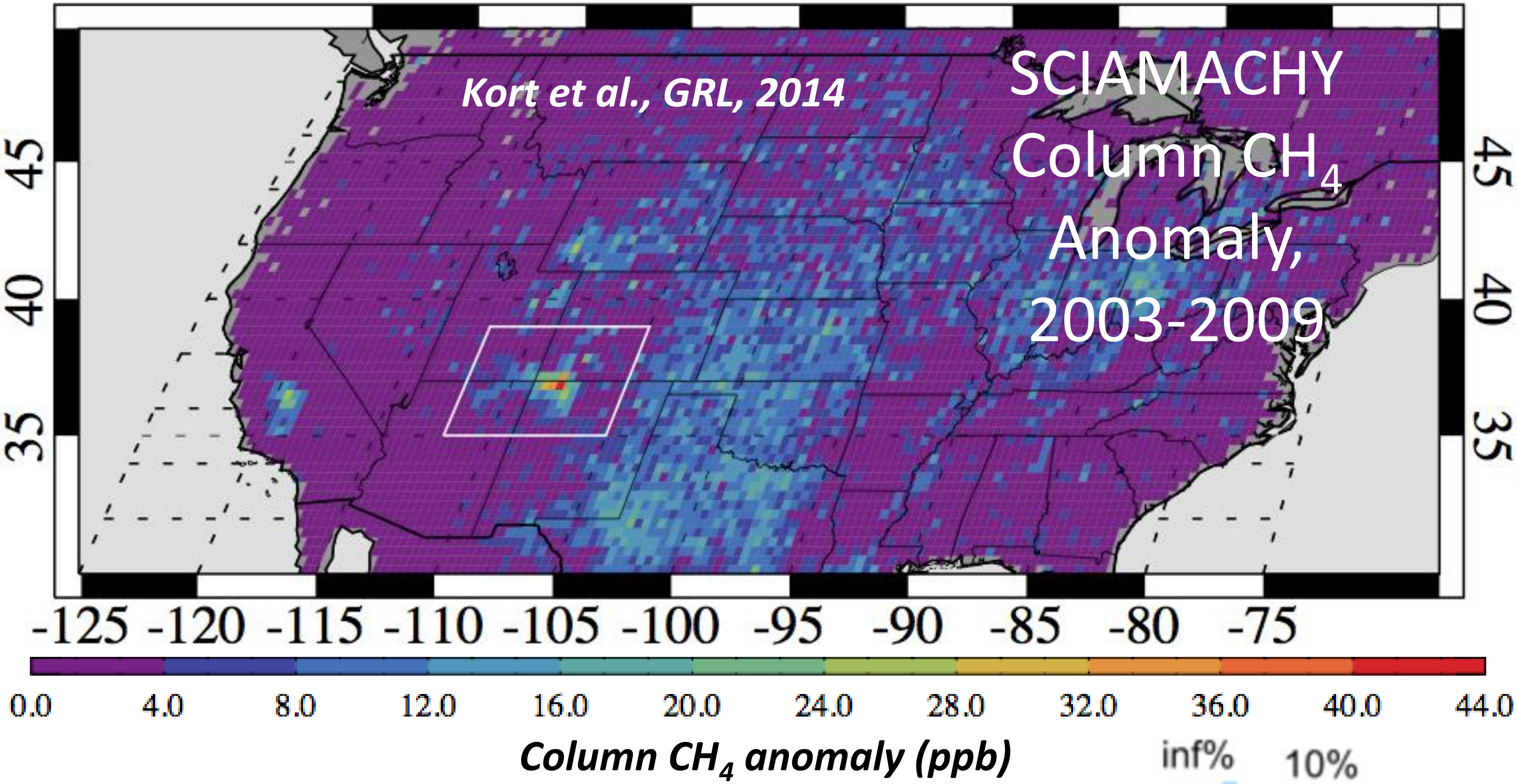


Fig. 3. The 2-y averaged CH_4 emissions estimated in this study (*A*) compared against the commonly used EDGAR 4.2 inventory (*B* and *C*). Emissions estimated in this study are greater than in EDGAR 4.2, especially near Texas and California.

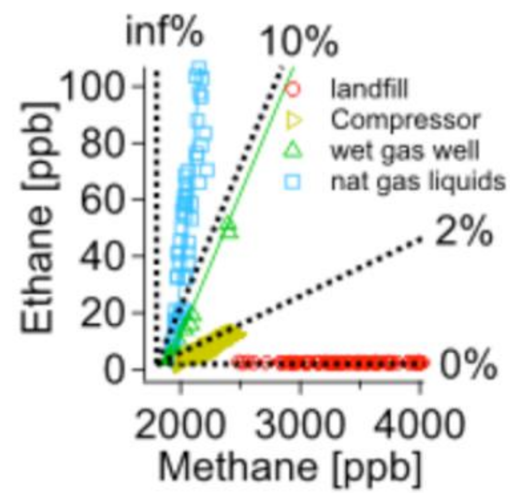
20020 | www.pnas.org/cgi/doi/10.1073/pnas.1314392110 Miller et al.

Miller et al. PNAS | December 10, 2013 | vol. 110 | no. 50 | 20021

Satellite CH_4 over Fossil Fuel Basins

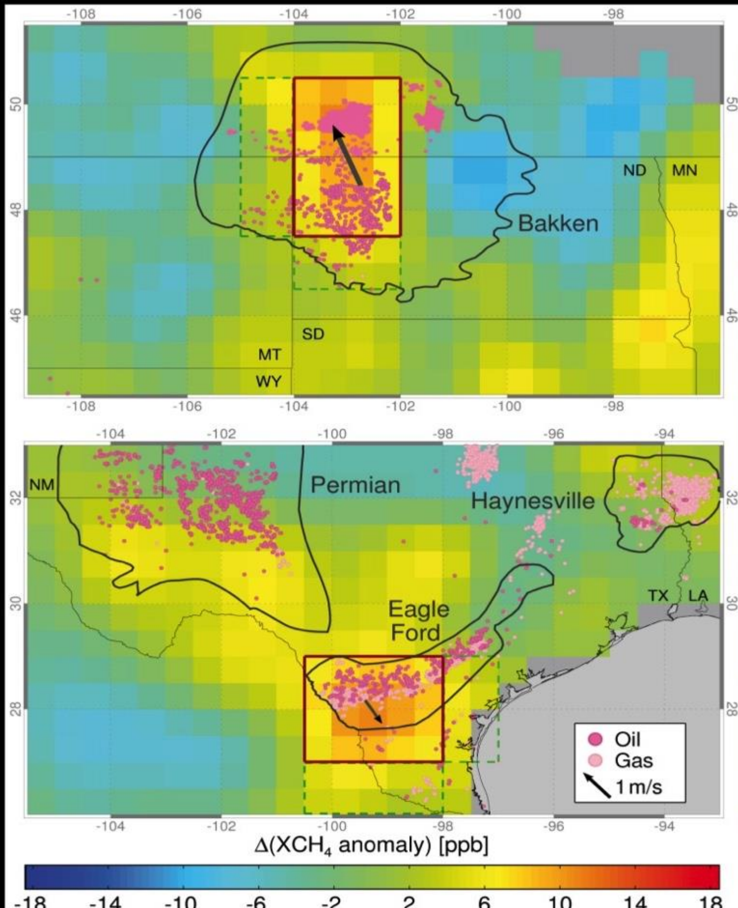


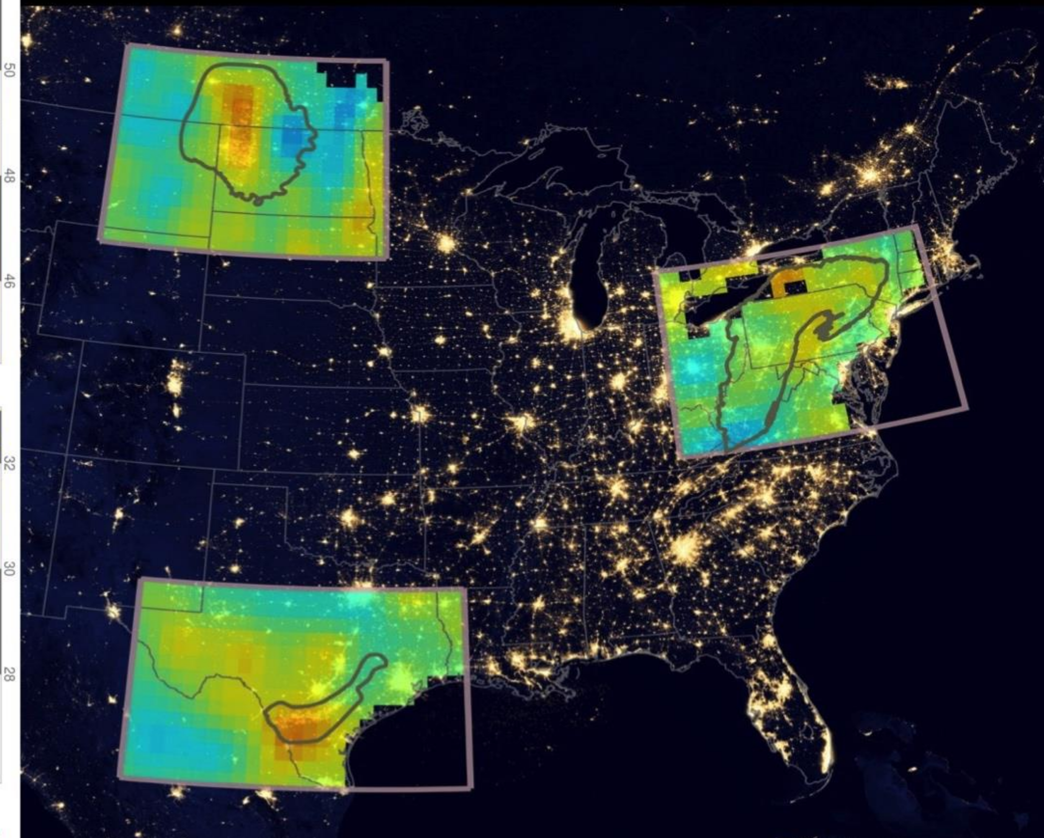
- Largest methane anomaly in the US
- Quantified annual emissions
- Independent verification by aircraft
- What are the sources?



Slide from Eric Kort

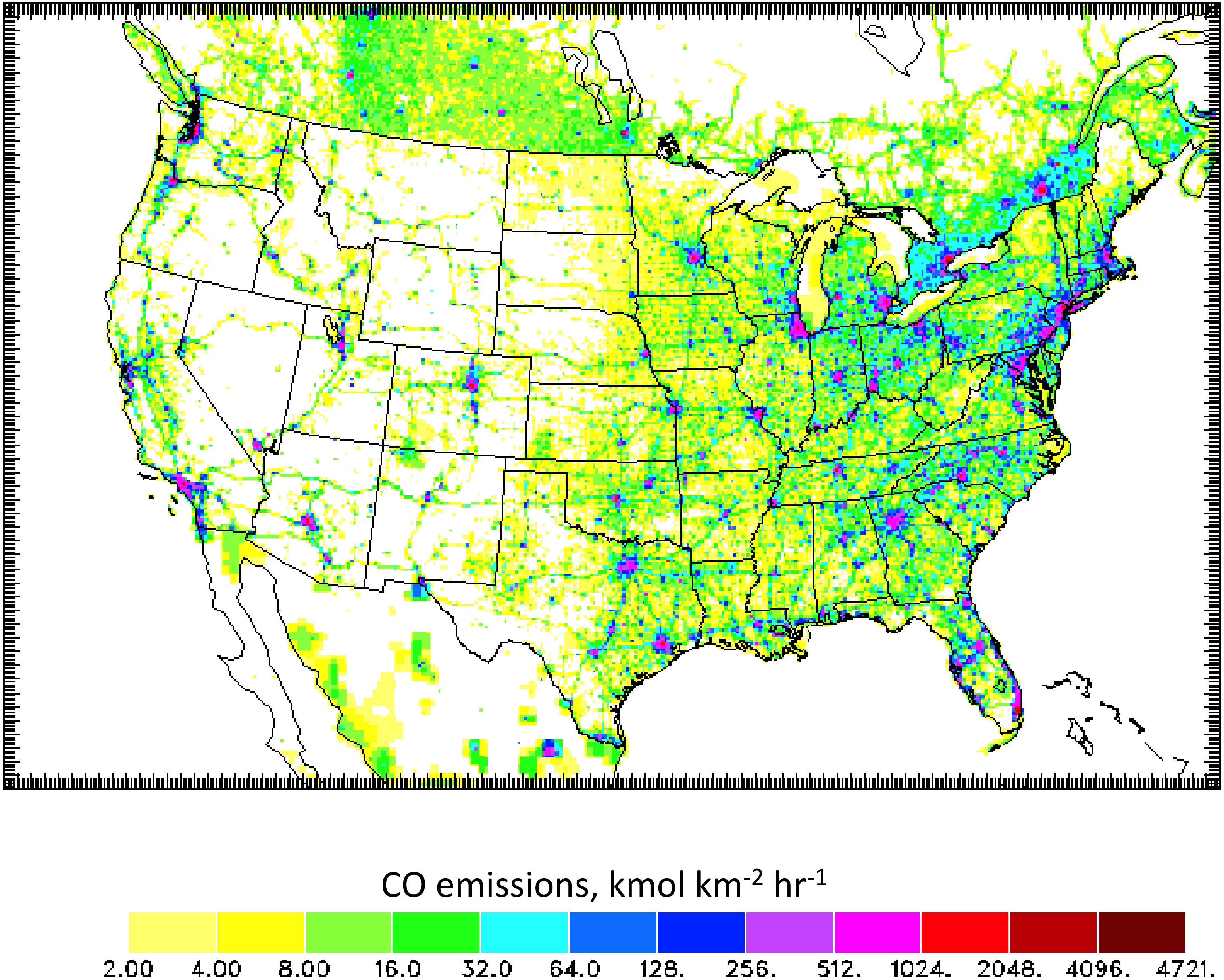
Fugitive methane emissions from oil and gas production (Schneising et al., 2014, Earth's Future)





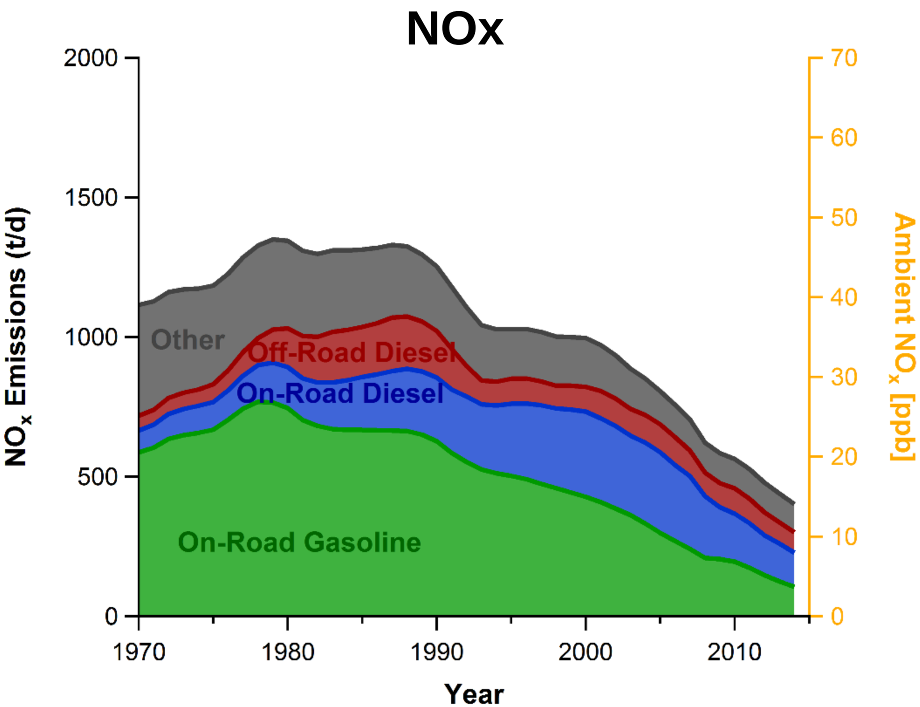
- To filter out large-scale seasonal variations or global increase, **XCH_4 anomalies** are computed by subtracting regional monthly means from the individual measurements.
- The shown **differences of the anomalies** for the period **2009-2011** relative to the period **2006-2008** highlight the changes in atmospheric methane abundance.
- Anomaly differences exhibit **increases aligning with the analysed oil and gas fields.**

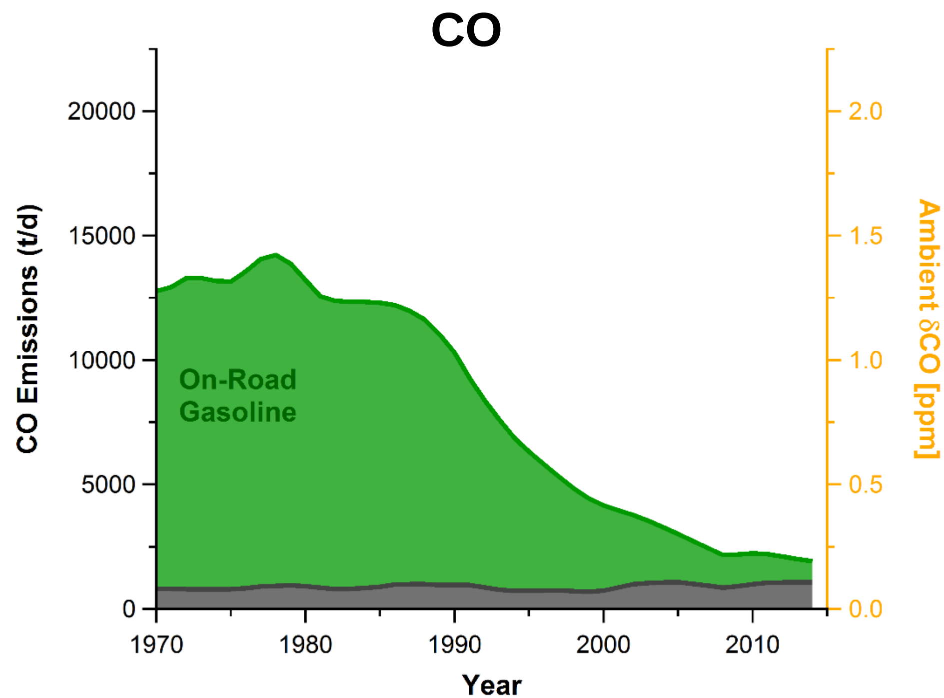
US CO Emissions



Fuel-Based Estimate of Mobile Source Emissions

Emissions = Fuel Use (kg) x Emission Factor (g/kg)



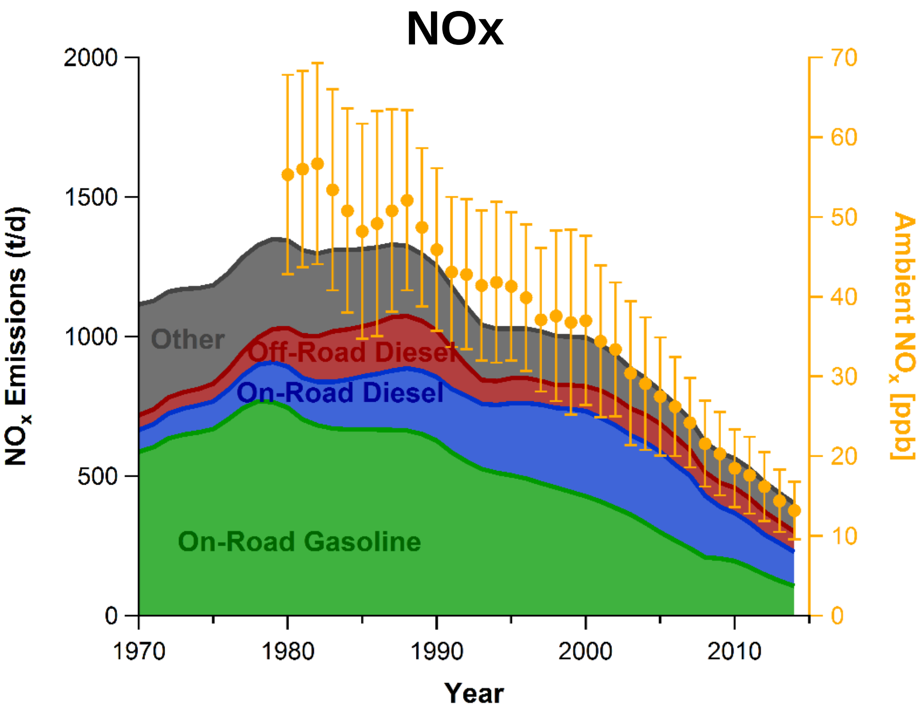


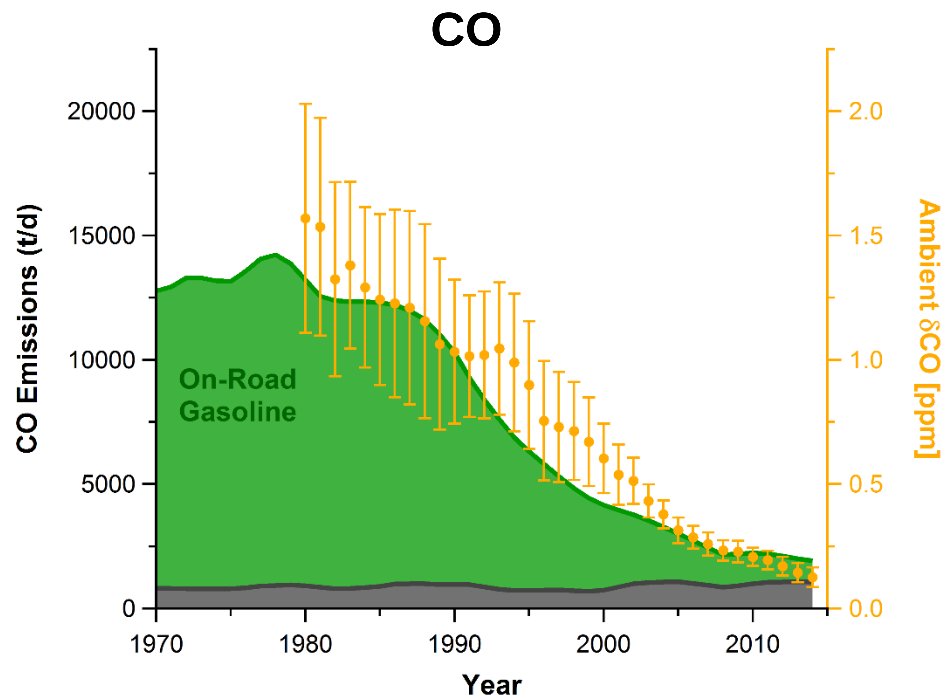
- On-road and off-road sources estimated using fuel-based approach
- Other sources taken from the official California inventory

McDonald et al. (2012, 2013)

Comparison with Long-Term Ambient Trends

Emissions = Fuel Use (kg) x Emission Factor (g/kg)





- On-road and off-road sources estimated using fuel-based approach
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McDonald et al. (2012, 2013)

NOAA OAR Earth System Research Lab

- ESRL carries out research and long-term monitoring to observe, understand and predict the Earth system
- Our stakeholders: researchers, forecasters, regulators, policymakers, decision-makers, private sector, the public

http://www.esrl.noaa.gov

Goals of ESRL Research

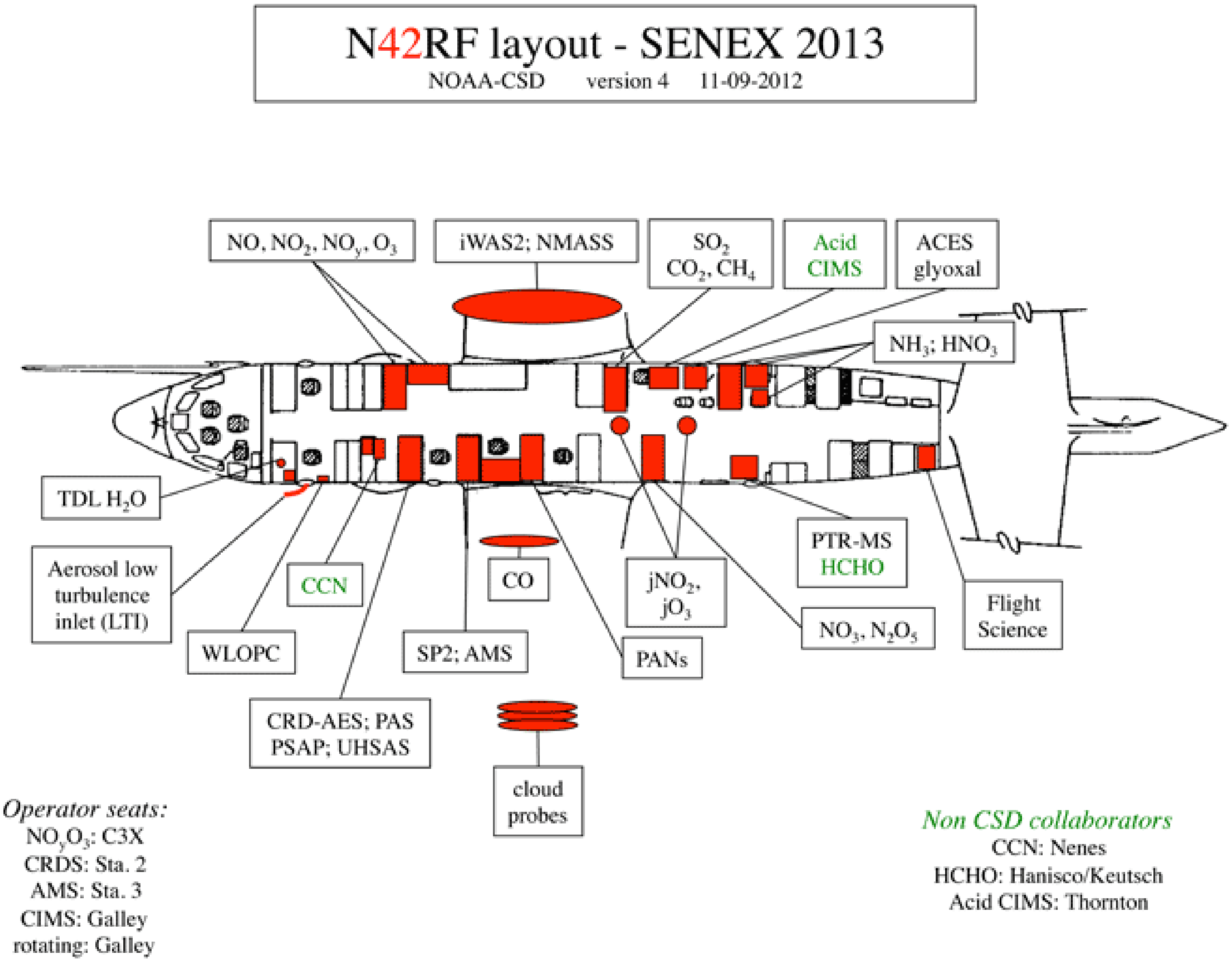
- Understand emissions, chemical processes, dynamics, and removal of atmosphere constituents
- Apply knowledge to environmental issues in the US and around the world
  - Climate change: CH_4, CO_2, BC,…
  - Air quality: O_3, PM, NOx, VOCs,…
  - Air toxics: aromatics, H_2S,…
  - Stratospheric issues: O_3 depletion
  - Interactions of all of the above

ESRL Research Assets

ESRL employs unique combination of observational platforms, analysis approaches, and human expertise

http://www.esrl.noaa.gov

NOAA WP-3 Instrument Layout



http://www.esrl.noaa.gov/csd/projects/senex/p3instruments.html

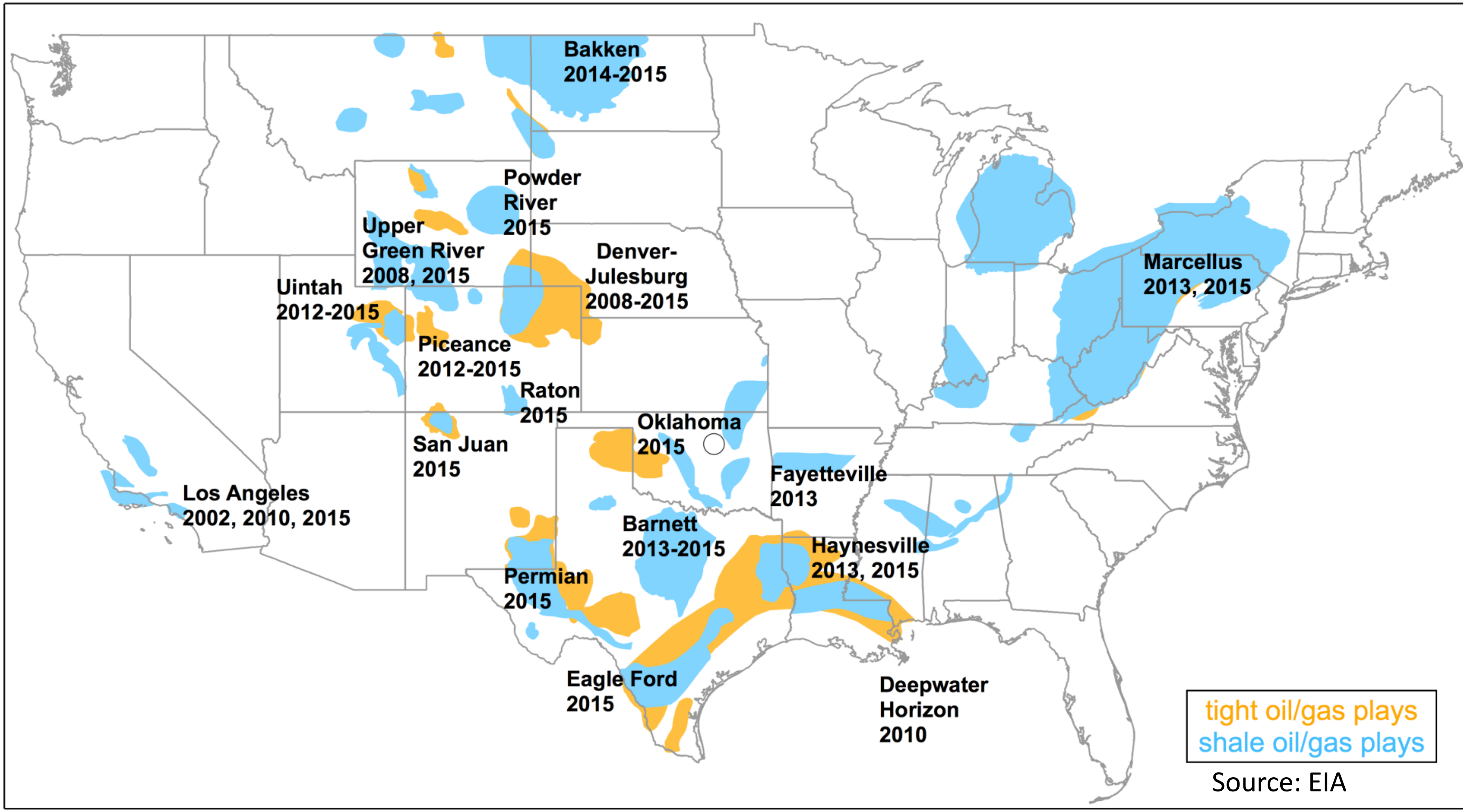
WRF-Chem Model

Settings for SENEX 2013 modeling

- Coupled meteorology-chemistry model, WRF-Chem version 3.7.1
- CONUS domain, 12km horizontal resolution, 50 vertical levels
- RACM_ESRL gas chemistry mechanism
- EPA NEI-2011 anthropogenic emissions, EDGAR and NEI-2011 CH_4 emissions
- Top-down emission estimates (5 shale basins only) of CH_4, NOx and VOCs for the oil/gas sector
- BEIS3.14 biogenic emissions

Ravan Ahmadov

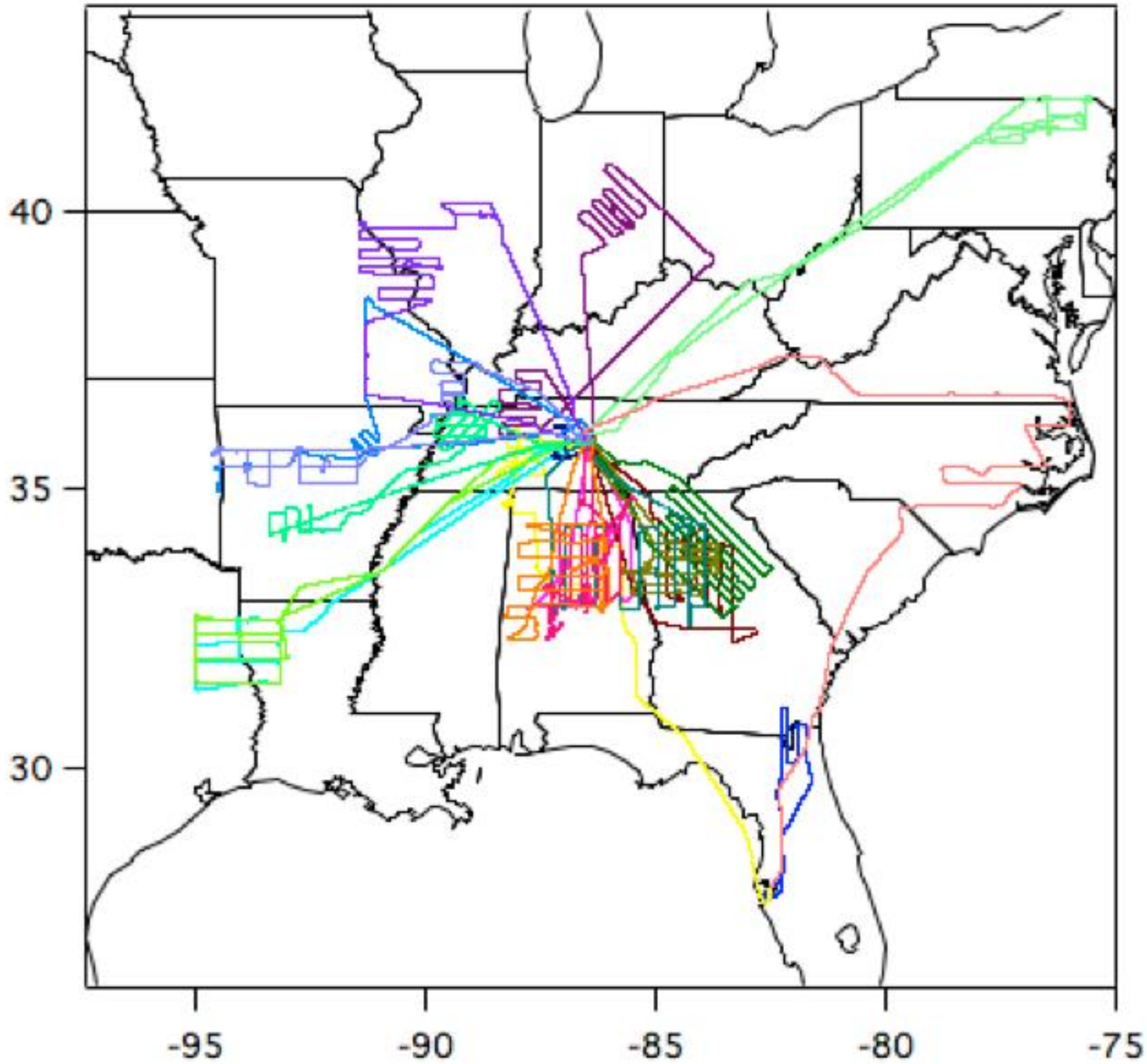
ESRL Oil/Gas Research Studies



Source: EIA

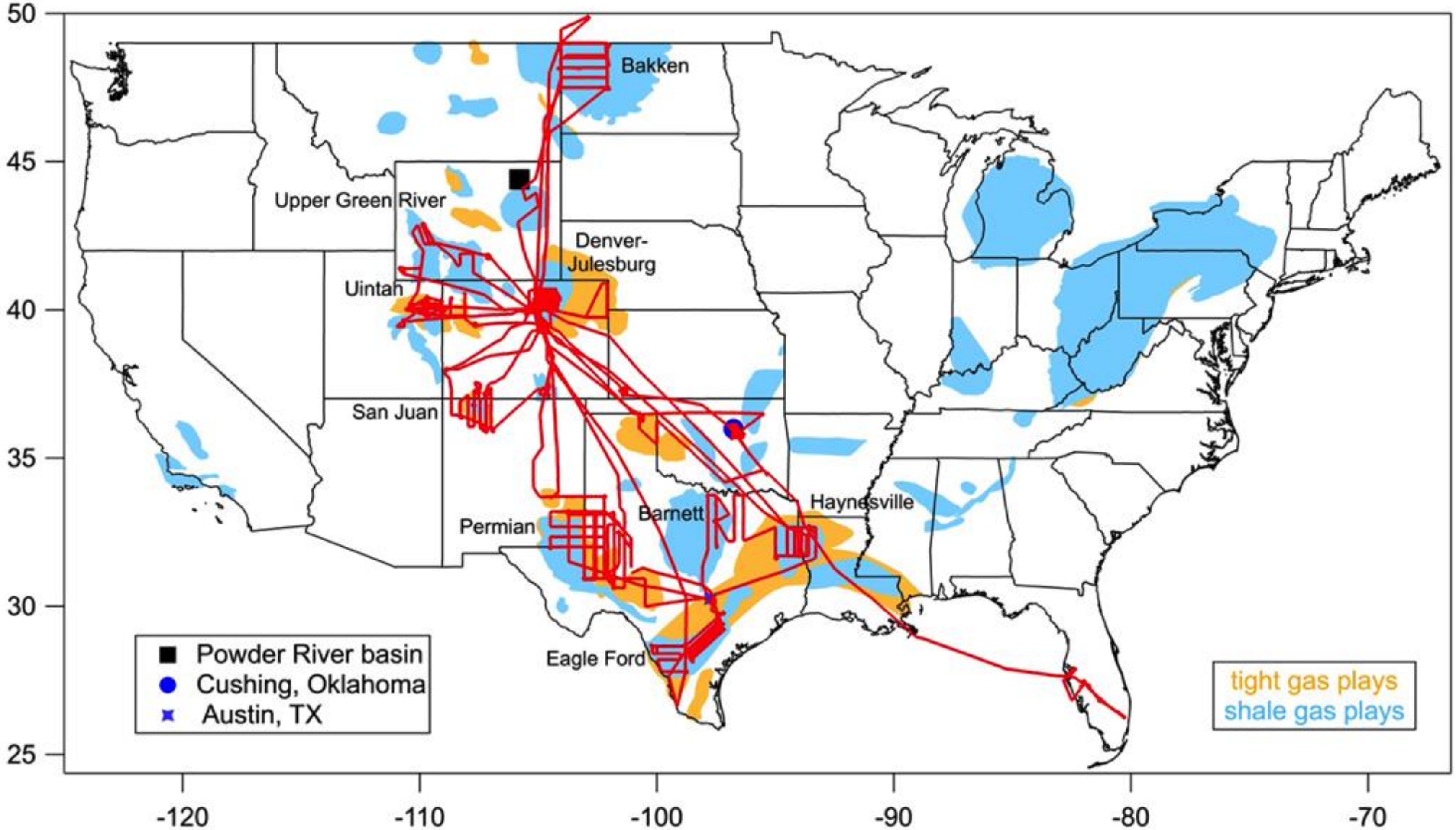
http://www.esrl.noaa.gov/csd/news/topics/oilandgas.html

SENEX 2013 NOAA WP-3 Flights



http://www.esrl.noaa.gov/csd/projects/senex/

SONGNEX 2015 NOAA WP-3 Flights



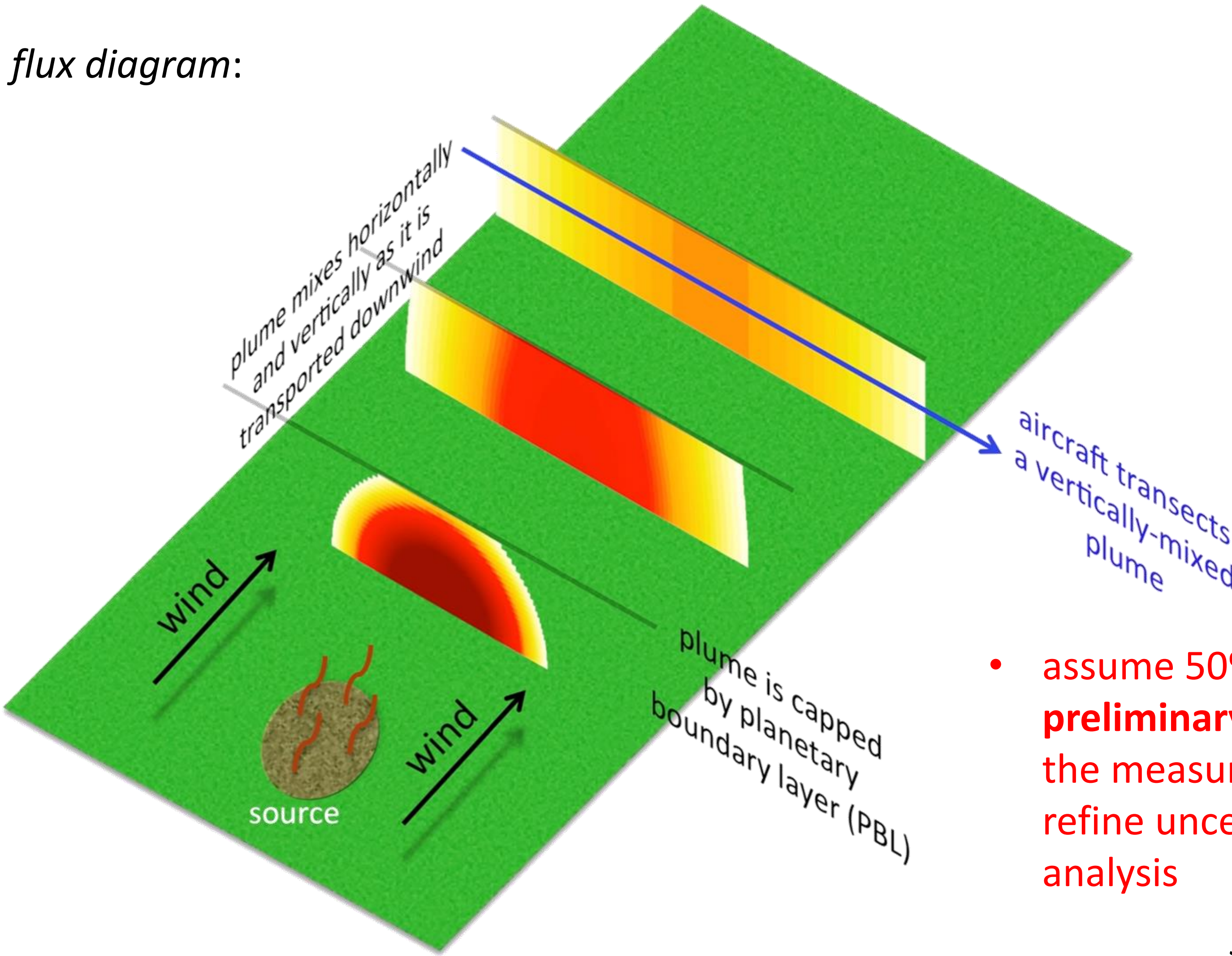
http://www.esrl.noaa.gov/csd/projects/songnex/

Aircraft Mass Balance Approach

$$\text{emitted mass}_i = v \bullet \int n_z\, dz \bullet \int X_i\, dy$$

= wind speed • PBL height • plume enhancement [*White et al.*, *Science*, 1976]

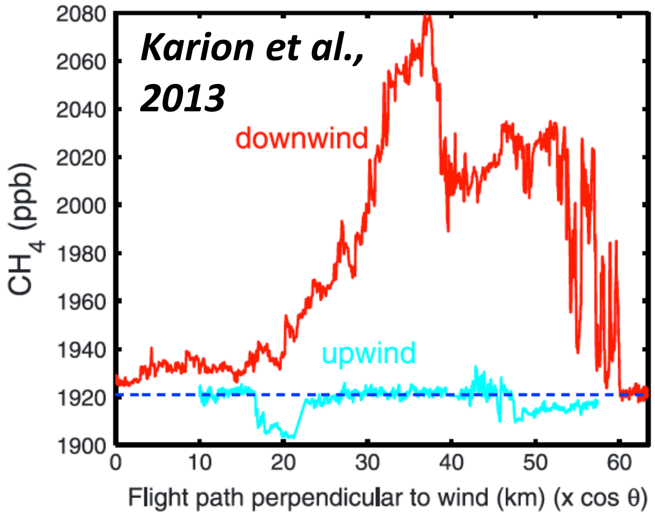
flux diagram:



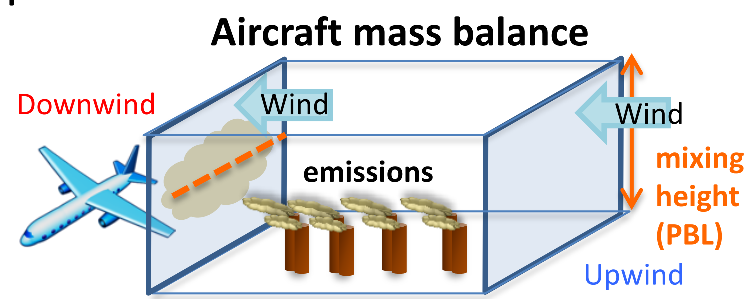
- assume 50% uncertainty for this **preliminary** analysis – we have the measurements needed to refine uncertainties in final analysis

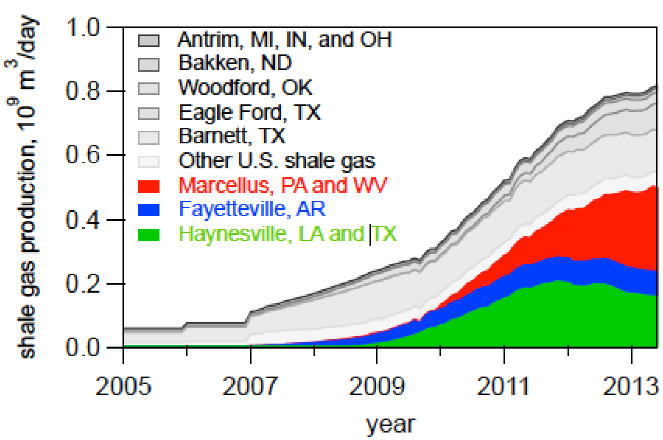
Slide from J. Peischl

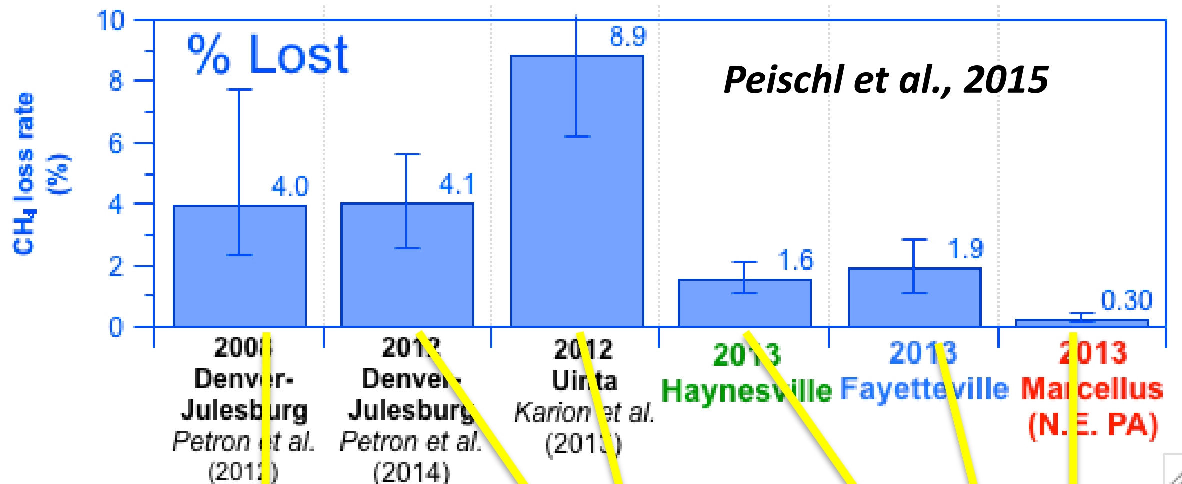
CH_4 Emissions in Oil/Gas Basins



Hydrocarbon leak rates inferred from observations in oil & gas production basins







Emissions from different oil & gas basins can differ significantly

Top-down estimates of oil/gas emissions for five basins

Uintah Basin Wintertime Ozone Study (2012, 2013)

Karion et al., GRL, 2013

CH_4 flux = 1450 ton/day

R. Ahmadov, et al., ACP, 2015

DJB

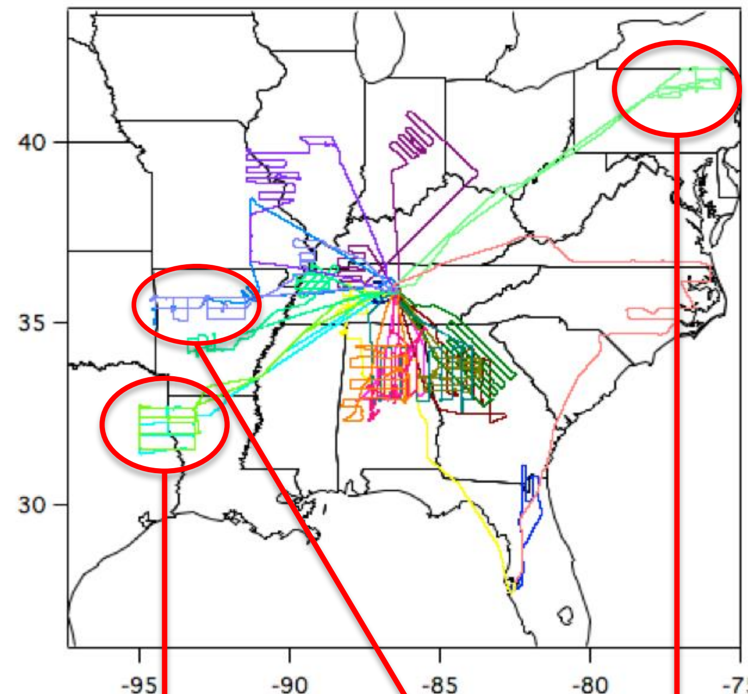
Summertime Ozone Near Natural Gas Emissions (SONNE) Denver-Julesburg Basin, 2012

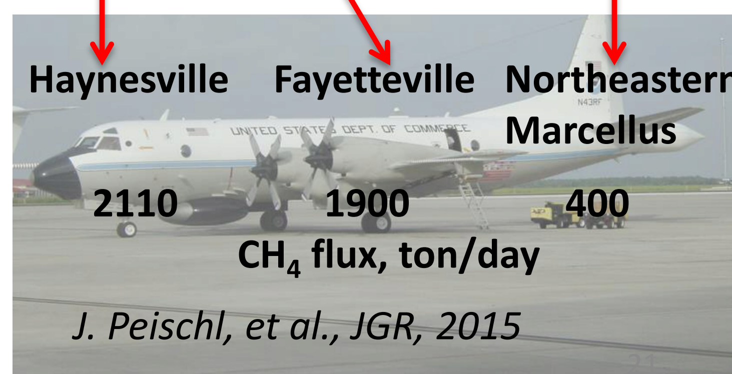
G. Petrón et al., JGR, 2014

CH_4 flux = 510 ton/day

J. Gilman, et al., EST, 2013

Southeast Nexus (SENEX) aircraft field campaign by NOAA June/July 2013, southeast U.S.





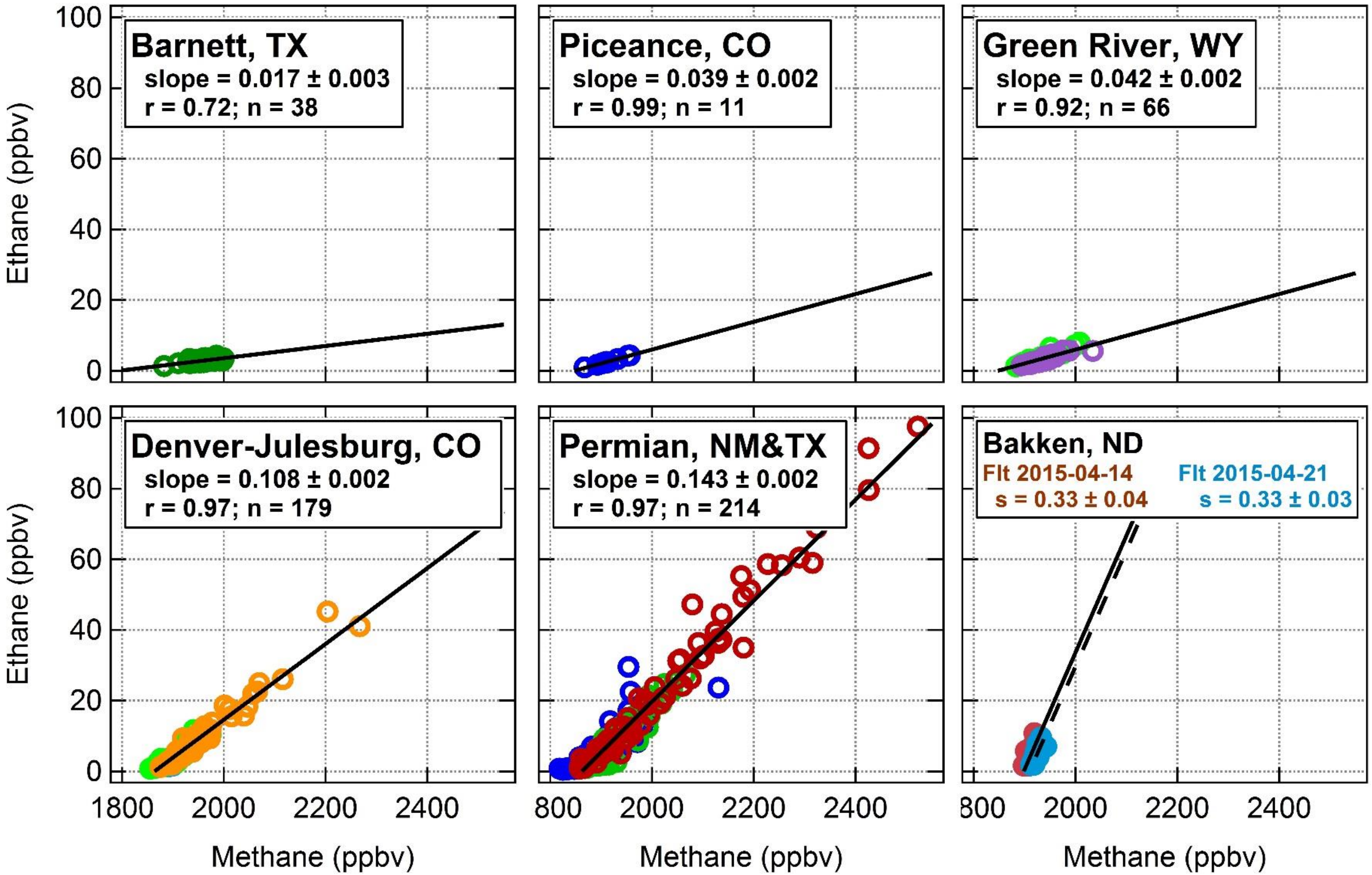
Haynesville	**Fayetteville**	**Northeastern Marcellus**
2110	**1900**	**400**

CH_4 flux, ton/day

J. Peischl, et al., JGR, 2015

$[VOC]/[CH_4]$ Enhancement Ratios in Oil/Gas Basins

VOC Enhancement Ratios: minimize effects of air mass mixing and dilution

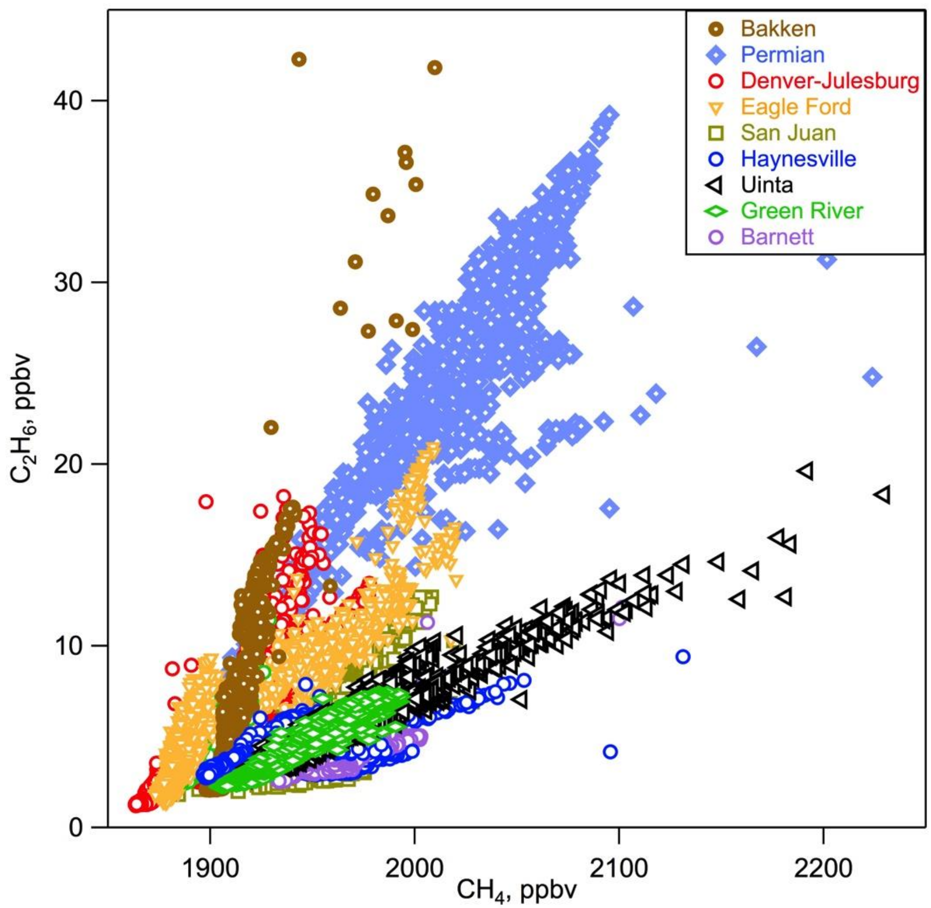


Jessica Gilman et al.

[Ethane]/[CH_4] Enhancement Ratios in Oil/Gas Basins

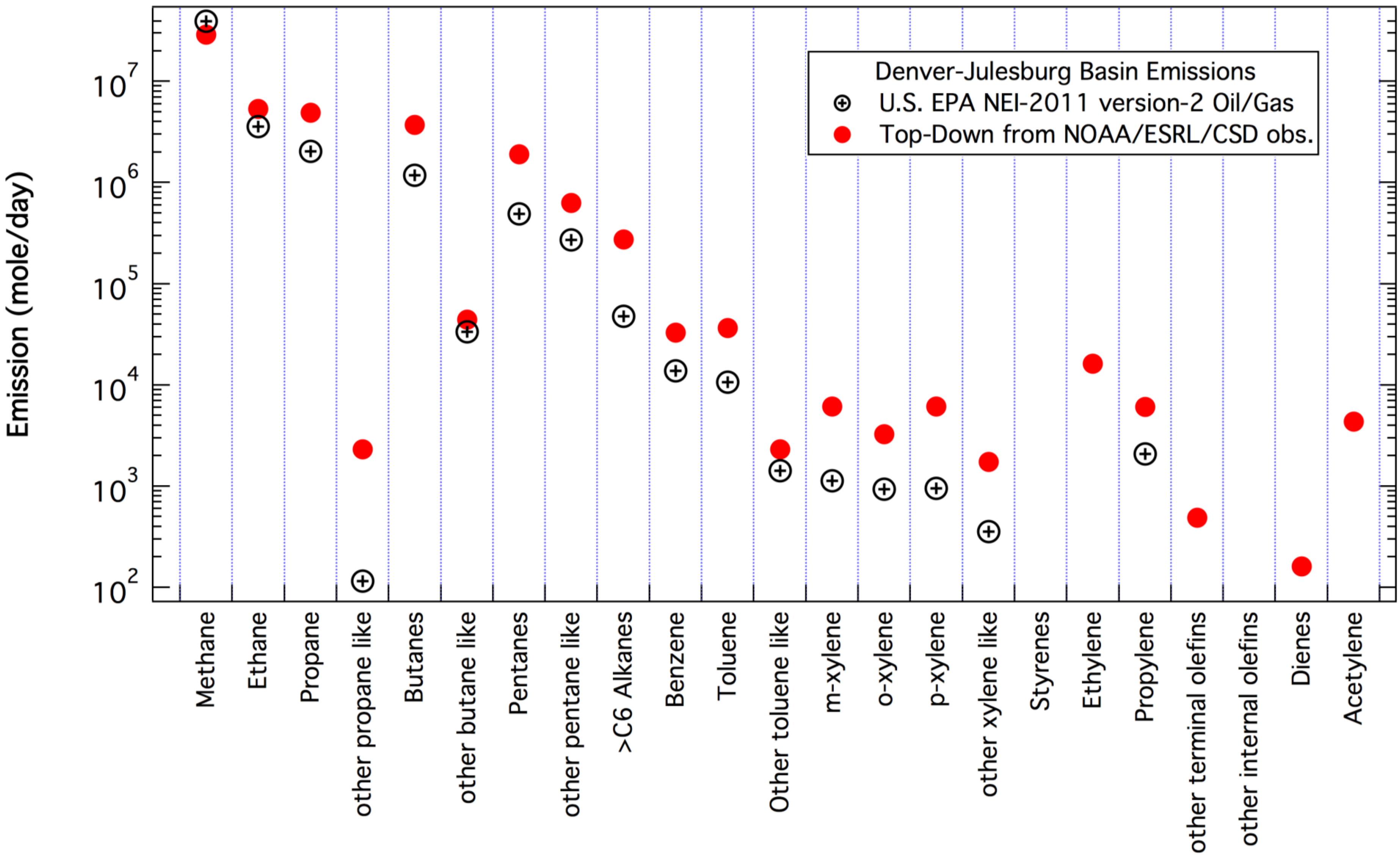
Fast ethane (C_2H_6) data: key to apportioning CH_4 emissions to specific sources

C_2H_6/CH_4 atmospheric enhancement ratio



Jeff Peischl et al.

Oil/Gas Emissions in NEI-2011v2 vs. Top-Down Estimates (Denver-Julesburg Basin, Colorado)

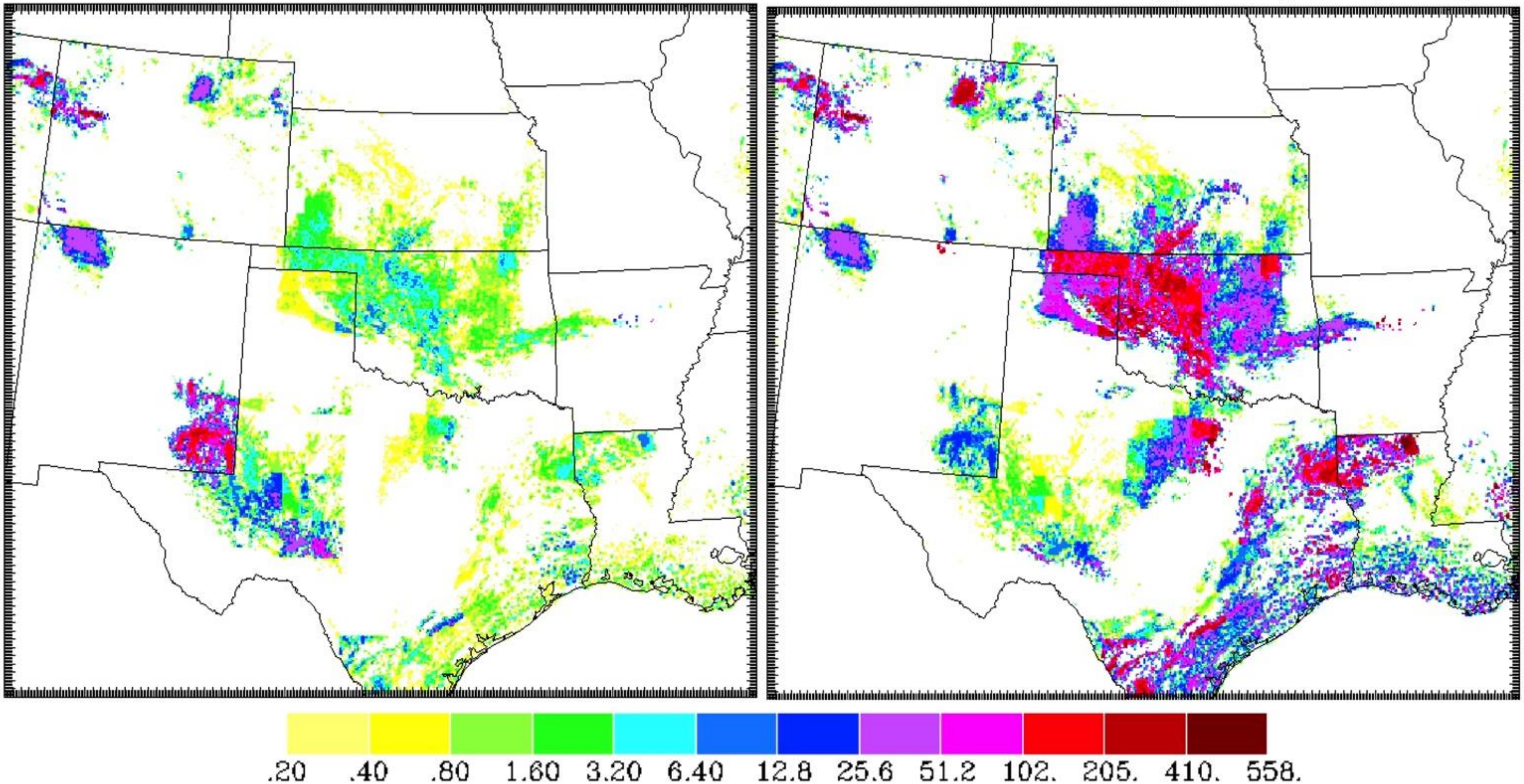


Emissions of aromatic VOCs are underestimated in the EPA inventory for all five shale basins.

Stuart McKeen et al.

Updates to Oil/Gas CH_4 Emissions in NEI2011 (changes based on ESRL measurements)

Version 1 Oil/Gas VOC/CH_4 profiles (Nov., 2013) **Version 2 Oil/Gas VOC/CH_4 profiles (March, 2015)**



(CH_4 flux (oil/gas sector only) kilomole/hr/4km-grid)

Stuart McKeen

Oil/gas Emissions for Uinta Basin, Utah

Emission datasets	Source	Methane (tons/year)	Non methane VOCs (tons/year)	NO_x (tons/year)
Bottom-up	EPA National Emission Inventory (NEI-2011)	100,279	101,184	16,448
Top-down	Based on the measurements	482,130	184,511	4,158

- ✓ Total top-down based methane flux estimate is from *Karion et al., 2013*
- ✓ Total methane and other VOC emissions in NEI-2011 are lower by a factor of 4.8 and 1.8

  than in the top-down estimates, respectively!
- ✓ Conversely, NO_x emissions are 4 times higher in the NEI-2011 inventory!

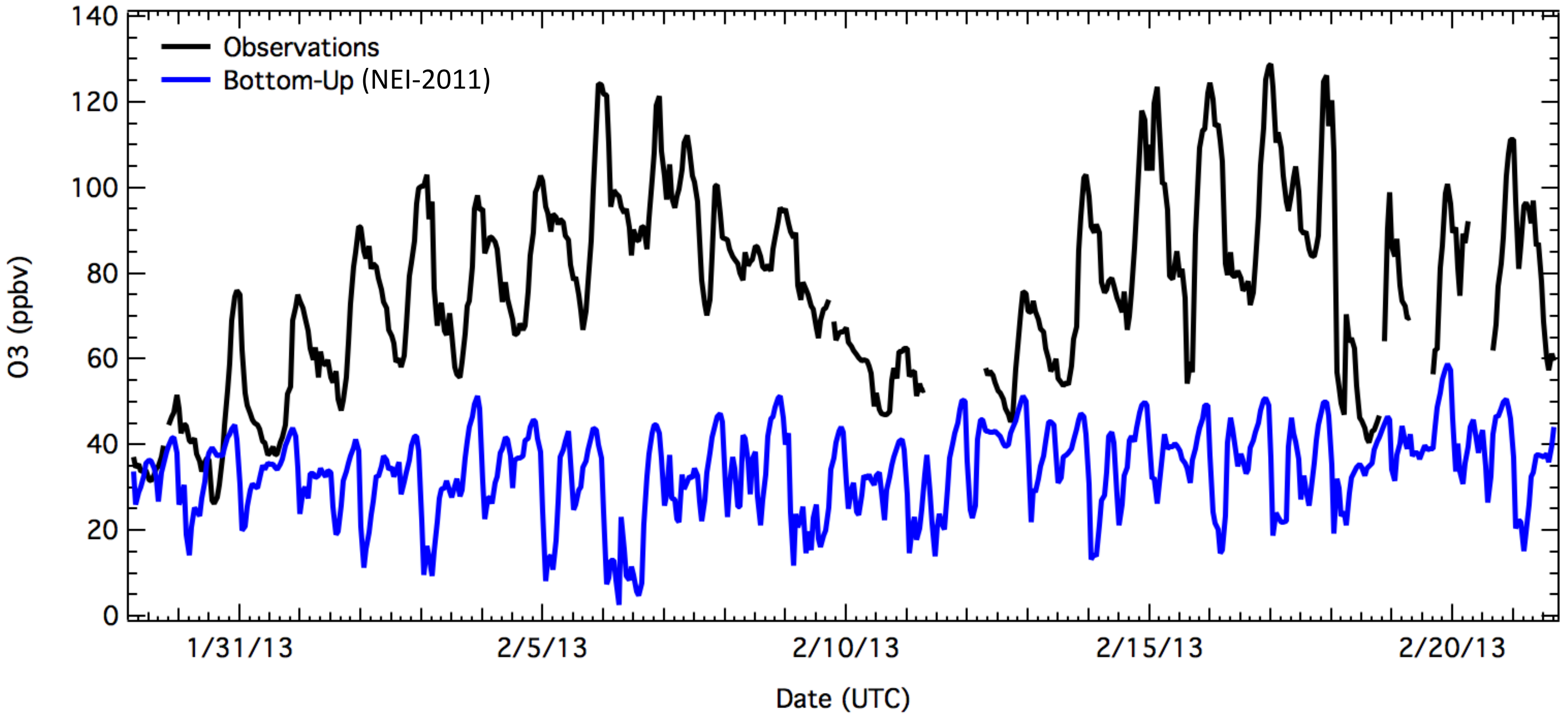
Implications for air quality regulations, climate and air quality studies!

Ahmadov et al., 2015 (ACP)

Observed vs. modeled O_3 time series: Uinta Basin, 2013

Multi-day buildup of surface O_3 during the stagnation episodes

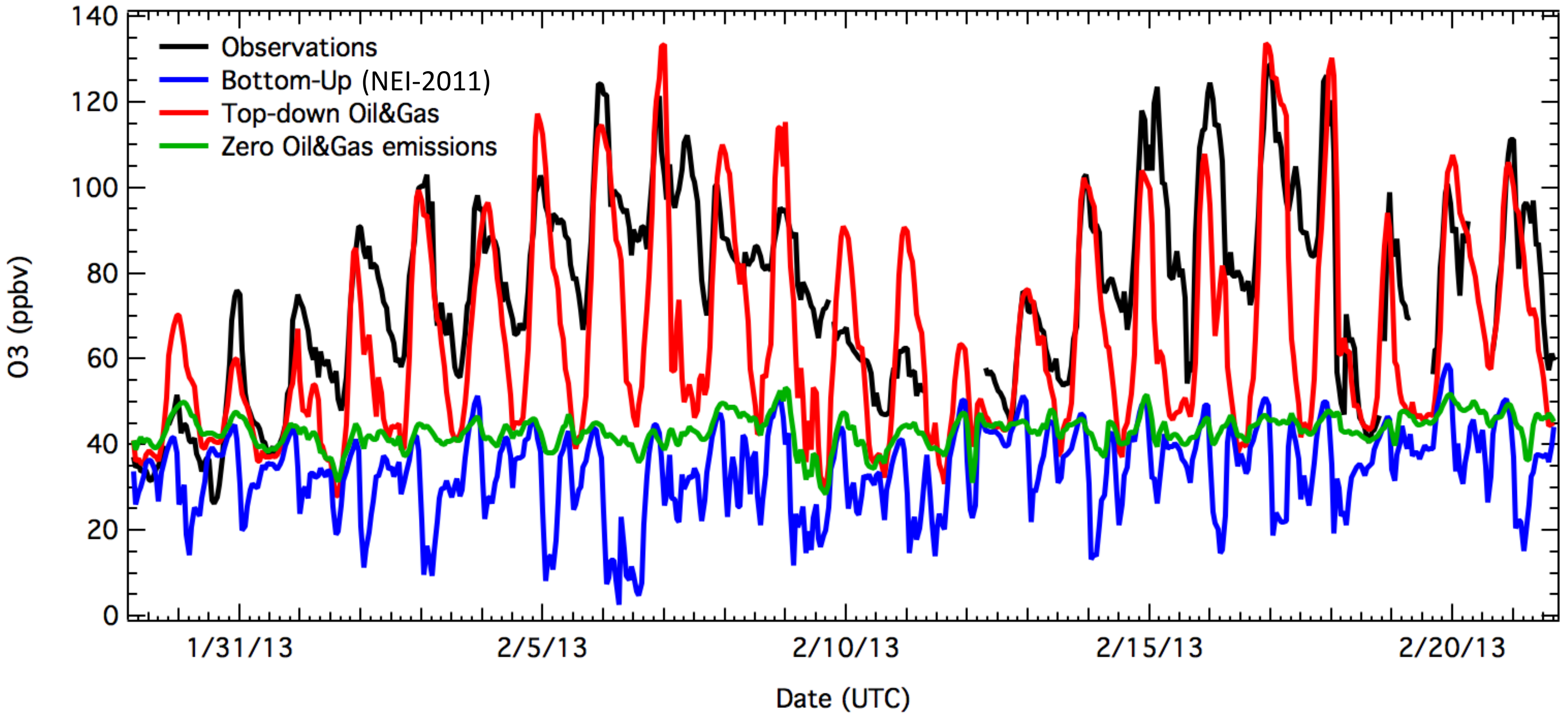
Model using EPA NEI-2011 emissions fails to reproduce observed high O_3 levels



Ahmadov et al. (2015), ACP

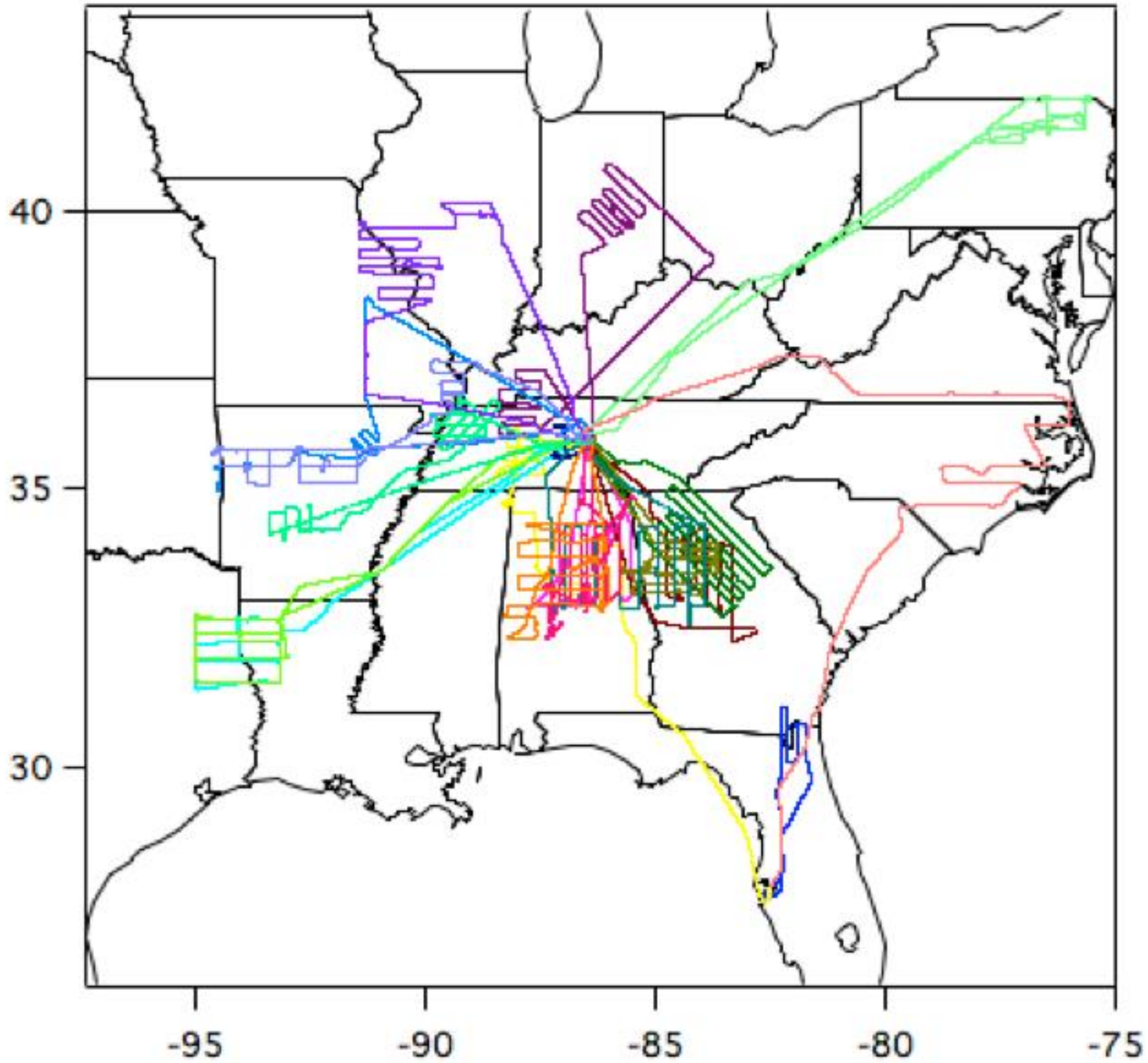
Observed vs. modeled O_3 time series: Uinta Basin, 2013

Only top-down emissions case can explain the high ozone levels
High ozone in the Uinta Basin is driven mostly by the oil/gas emissions



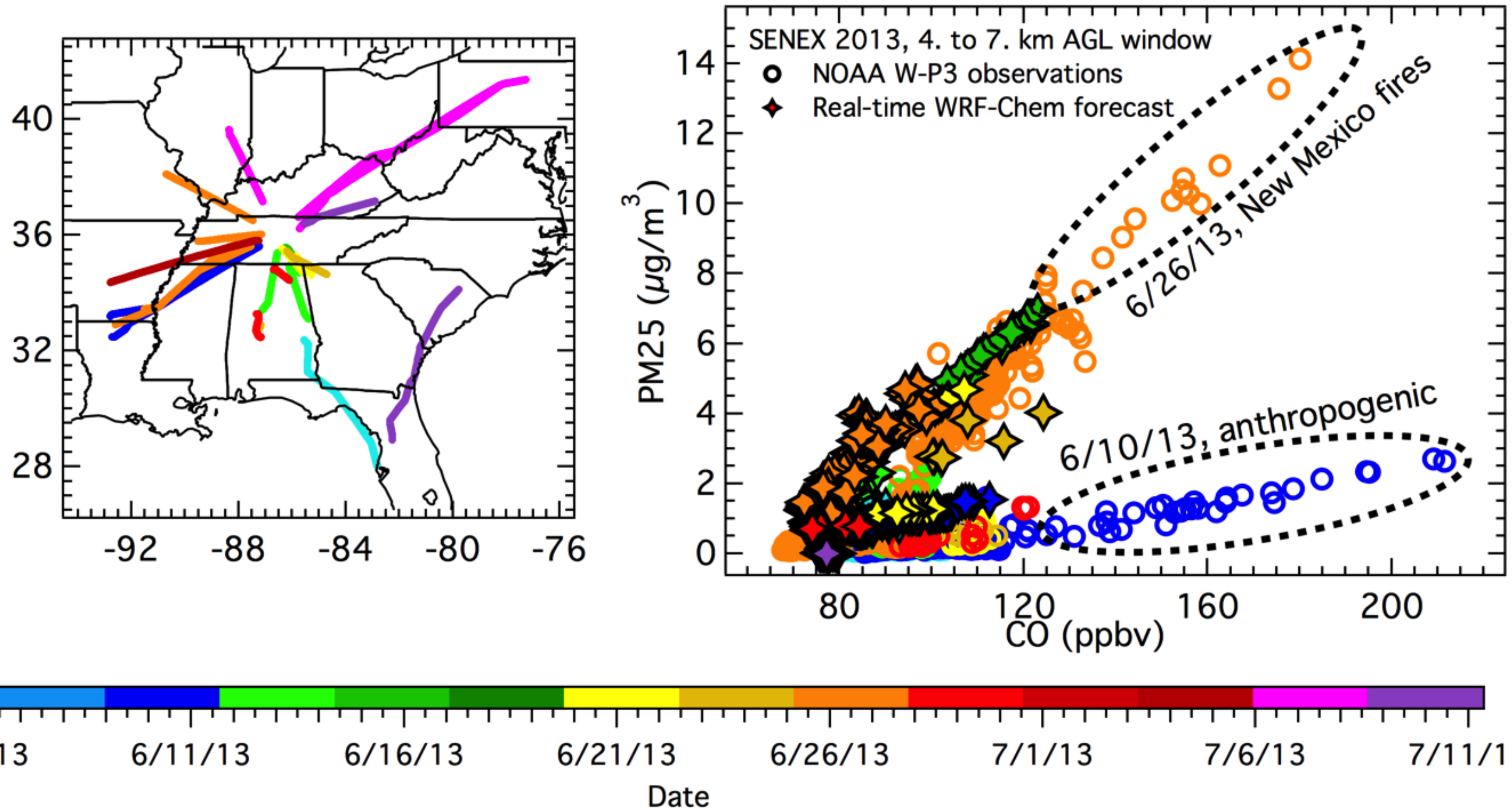
Ahmadov et al. (2015), ACP

SENEX 2013 NOAA WP-3 Flights



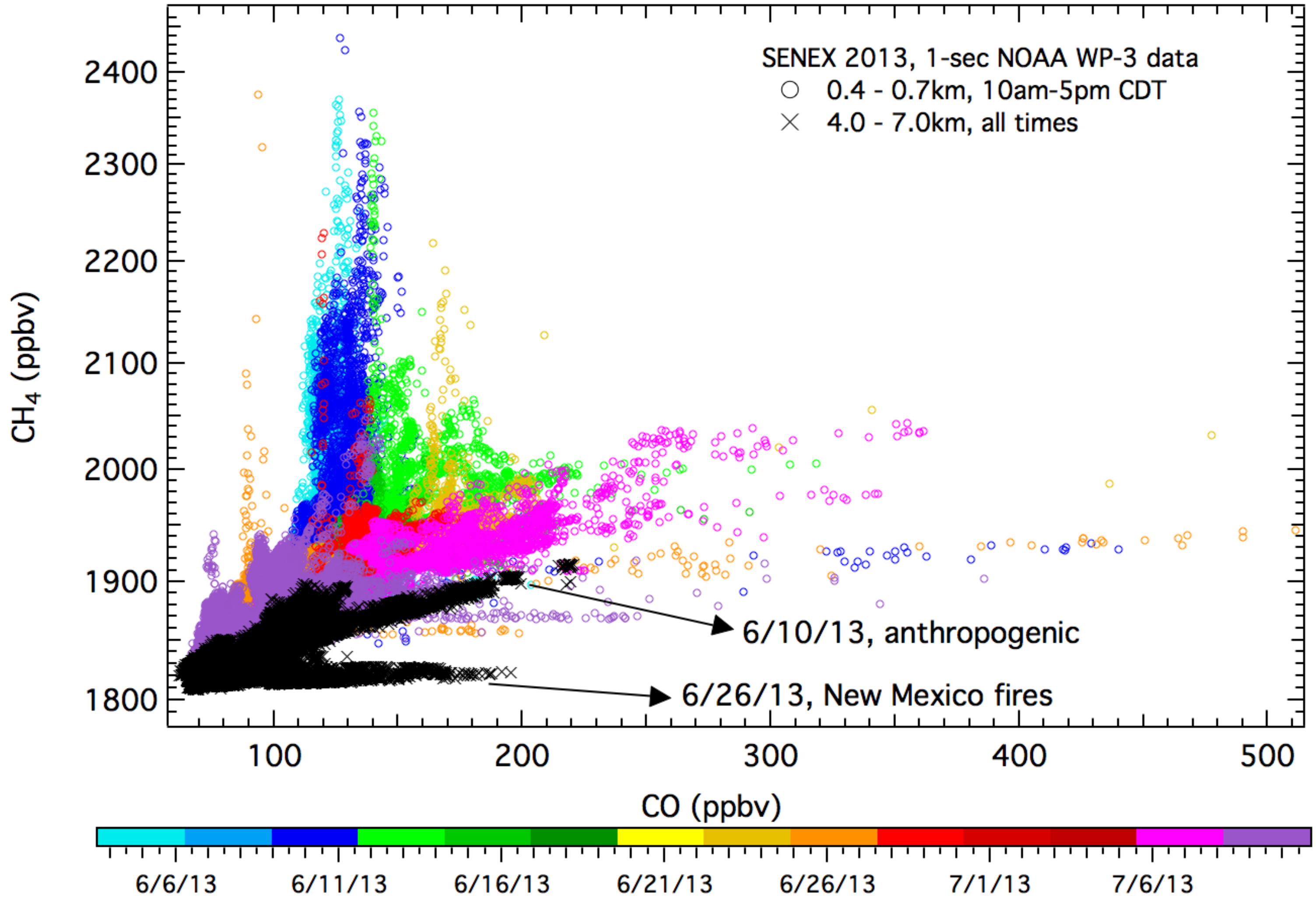
http://www.esrl.noaa.gov/csd/projects/senex/

Understanding Sources during SENEX



Stuart McKeen et al.

Understanding Sources during SENEX

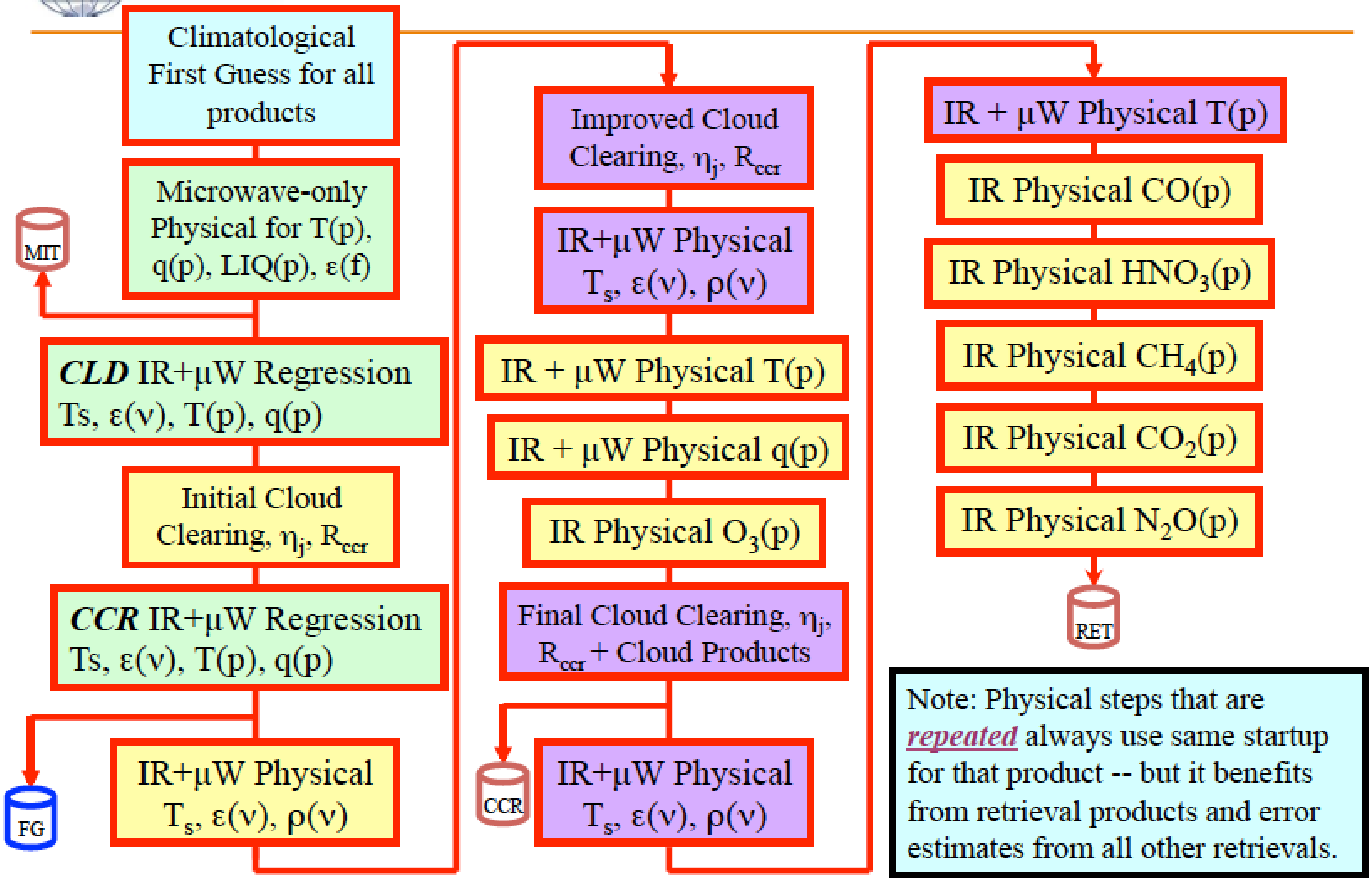


Stuart McKeen

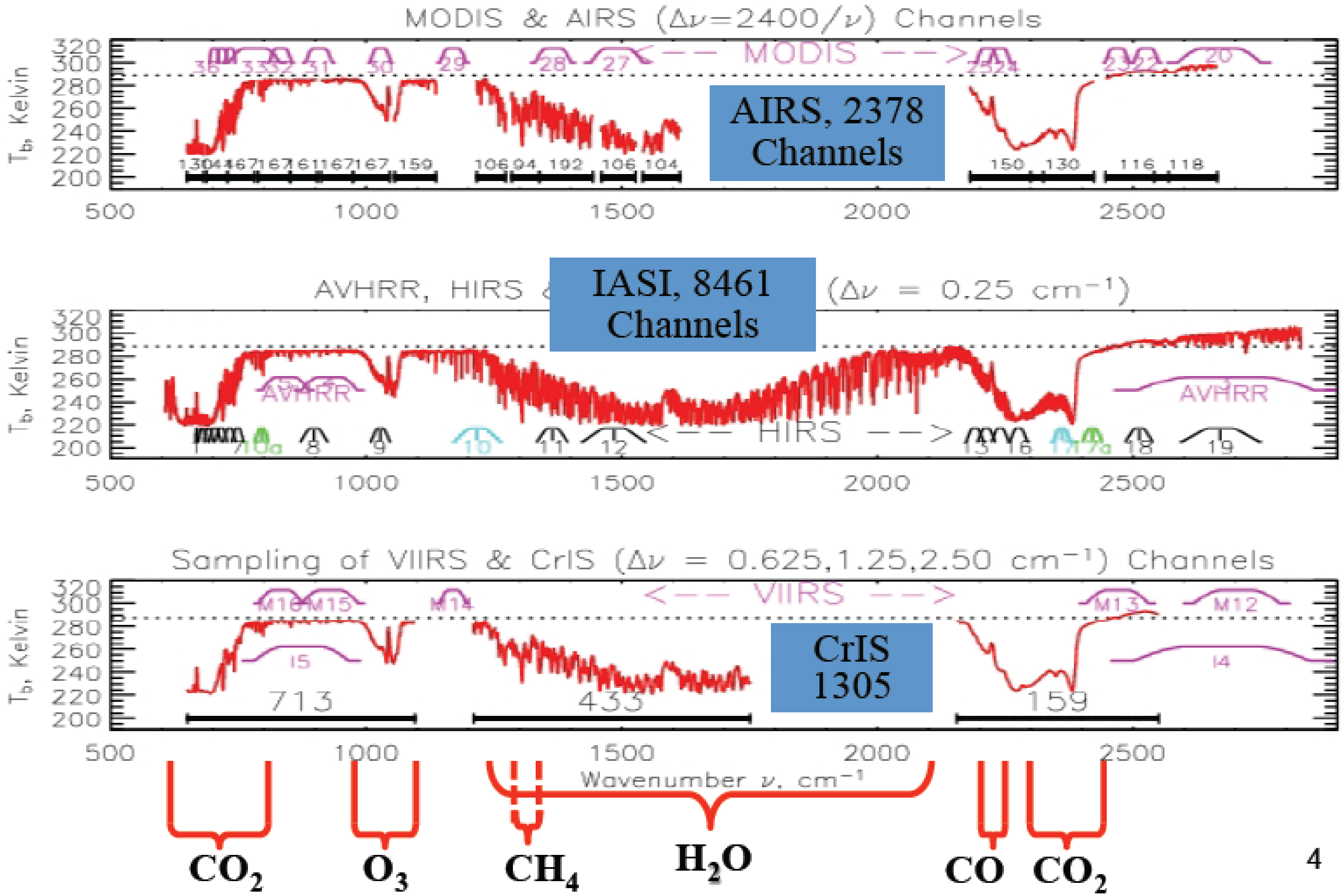
What is NUCAPS?

- NUCAPS is the operational code for CrIS+ATMS retrievals
- Goal of this work is to implement the science version of NUCAPS into direct broadcast
  - Science version products are identical to operational code
    - Science retrieval code is literally run through a filter to become the operational code
      - easy to perform regression tests to verify performance.
    - Operational preprocessor was converted to IDL
    - Backward compatibility is maintained (can run all previous versions of the operational code, up to bugs)
  - Science version has many enhancements
    - Options for a plethora of diagnostic information
    - Research configurations (*i.e*, retrieval steps are configurable)

Flow Diagram of NUCAPS Retrieval Steps



Spectral Coverage of Thermal Sounders & Imagers (Example Aqua, Metop, Suomi-NPP)

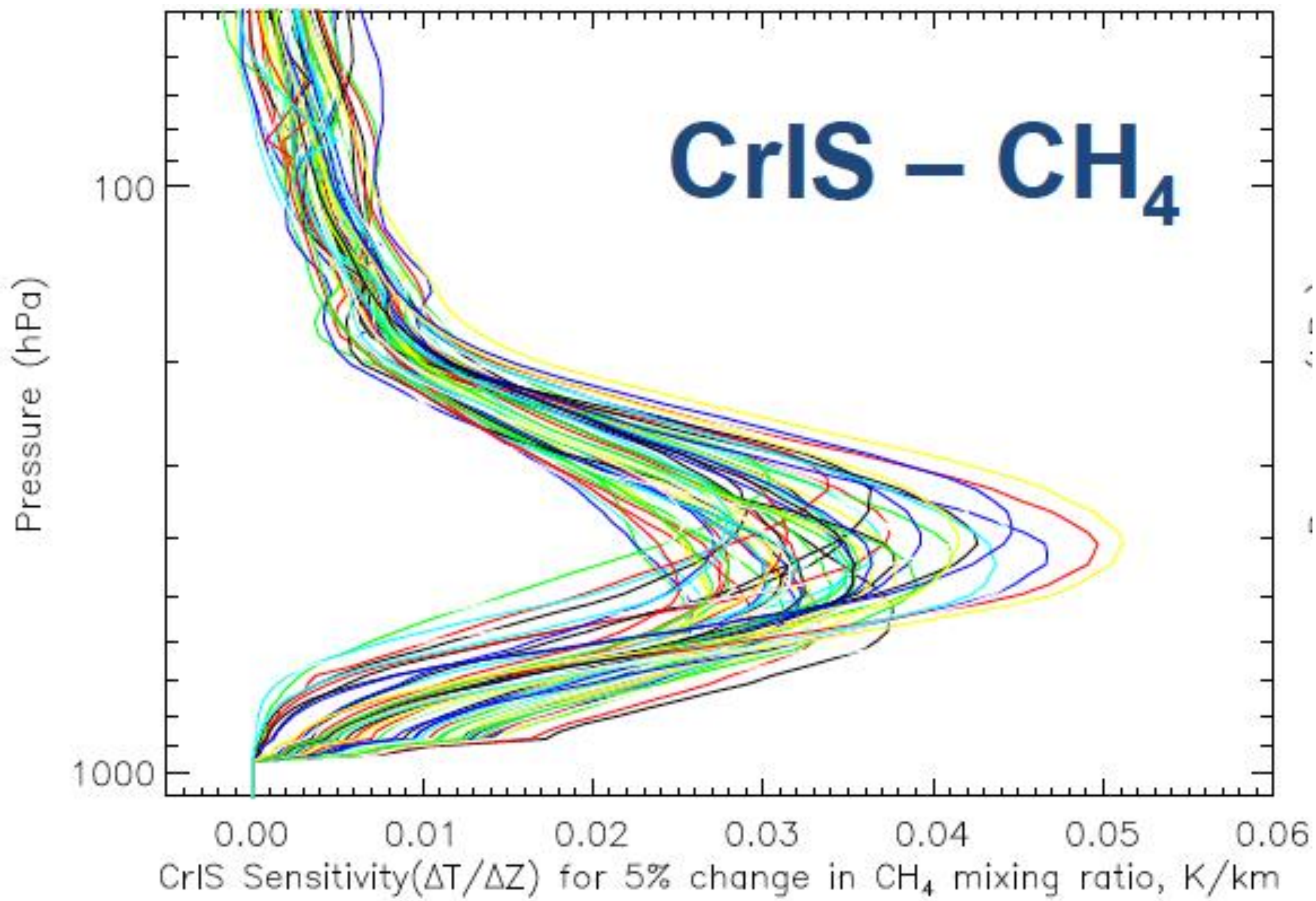


Chris Barnet et al., CrIS Trace Gas Data Users Workshop, 18 Sept 2014

Summary of products from AIRS, IASI and NUCAPS Algorithm

gas	Range (cm^{-1})	Precision	d.o.f.	Interfering Gases	Sensitivity
T	650-800 2375-2395	1.5K/km	6-10	H2O,O3,N2O emissivity	surface to ~1 mb
H_2O	1200-1600	15%	4-6	CH4, HNO3	surf to 300 mb
Cloud P, T, fraction	700-900	25 mbar, 1.5K, 5%	≈2	CO2, H2O	surface to tropopause
O_3	1025-1050	10%	1+	H2O,emissivity	Lower strat.
CO	2080-2200	15%	≈ 1	H2O,N2O	Mid-trop
CH_4	1250-1370	1.5%	≈ 1	H2O,HNO3,N2O	Mid-trop
CO_2	680-795 2375-2395	0.5%	≈ 1	H2O,O3 T(p)	Mid-trop
Volcanic SO_2	1340-1380	50% ??	< 1	H2O,HNO3	flag
HNO_3	860-920 1320-1330	50% ??	< 1	emissivity H2O,CH4,N2O	Upper trop
N_2O	1250-1315 2180-2250	5% ??	< 1	H2O H2O,CO	Mid-trop

CrIS CH_4 Vertical Sensitivity

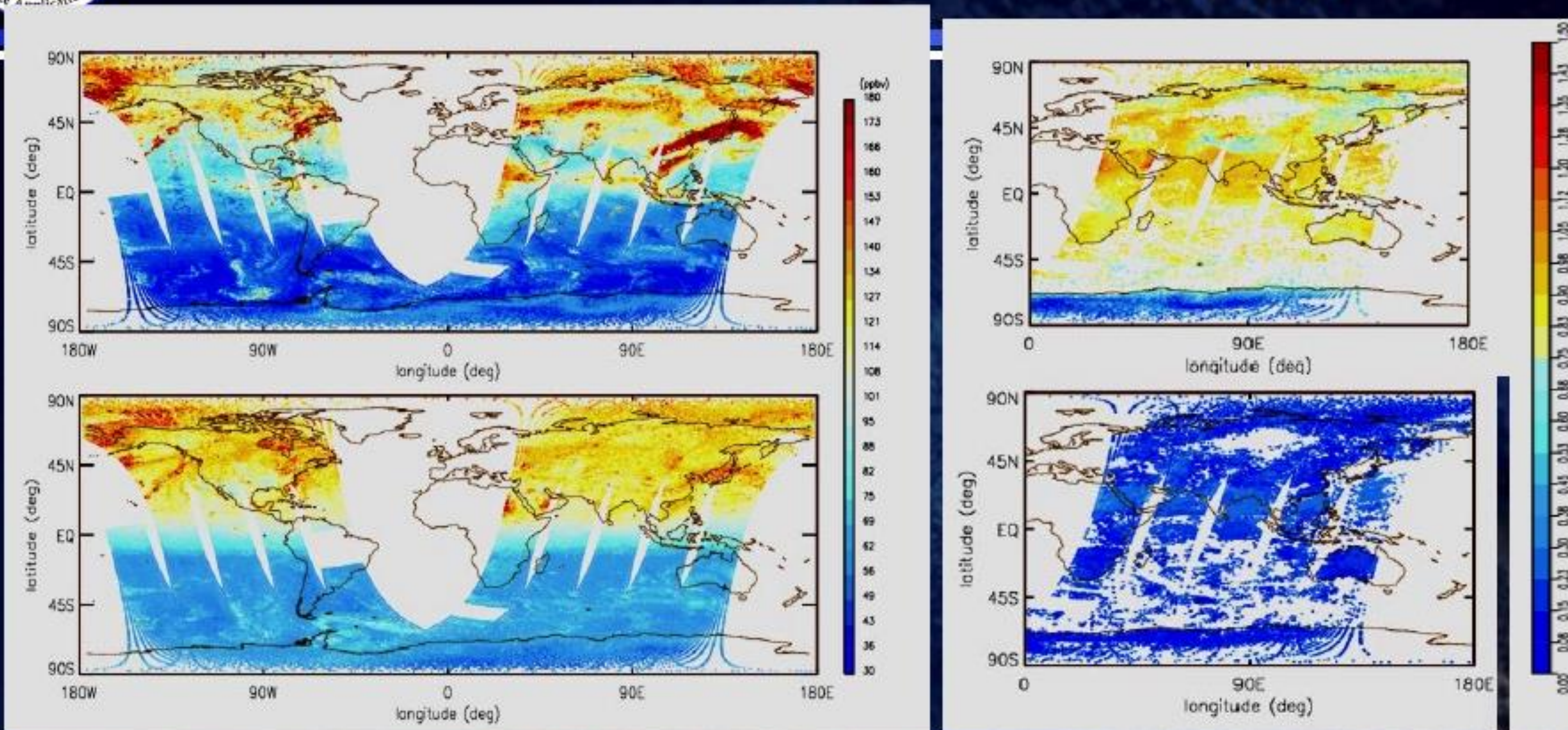


Xiaozhen Xiong et al., CrIS Trace Gas Data Users Workshop, 18 Sept 2014

CO high resolution (top) vs operational low resolution results (bottom)

NUCAPS CO retrieval (~450mb)

CO DOF



- High resolution mode retrievals show significantly more structure in the global distribution of CO abundance with respect to the low resolution mode.
- NUCAPS high spectral resolution CO DOFS (top right) are observed to consistently improve across all latitudinal regimes, up to one order of magnitude wrt the low resolution DOFS (bottom right).
- This higher information content enables a larger departure from the a priori, hence the increased spatial variability observed in the high spectral resolution map wrt the low resolution map.

Antonia Gambacorta et al., AMS Annual Meeting, 6 Feb 2014

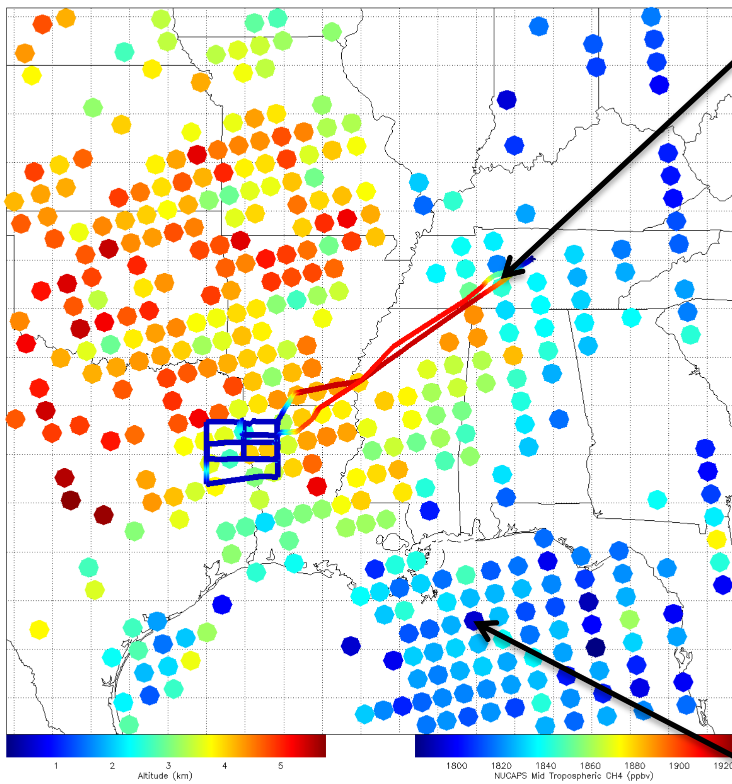
Availability of NUCAPS vs Aircraft Data

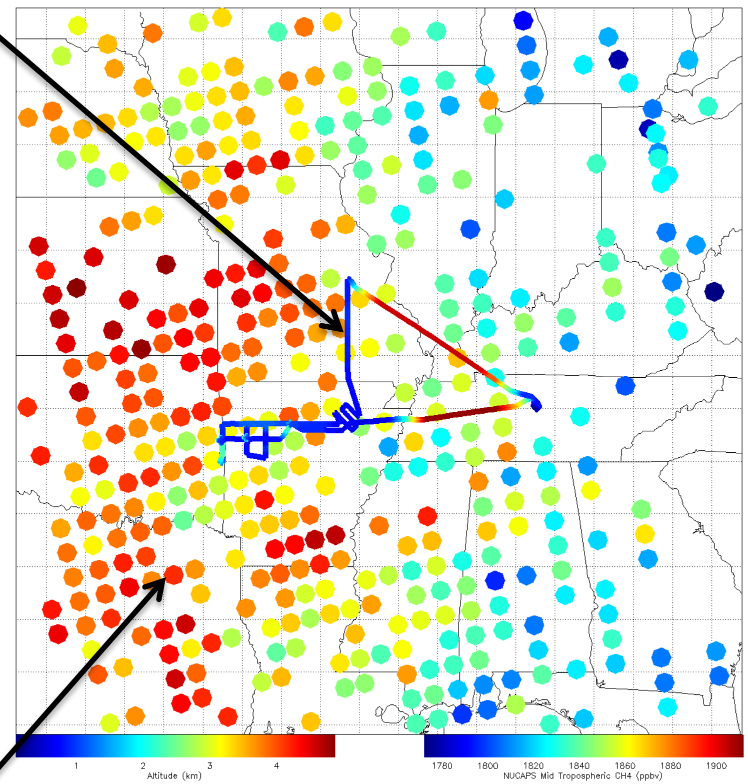
Limited opportunities for direct comparisons of aircraft and NUCAPS data during SENEX and other field intensive periods

10 June 2013

Aircraft flight tracks

26 June 2013

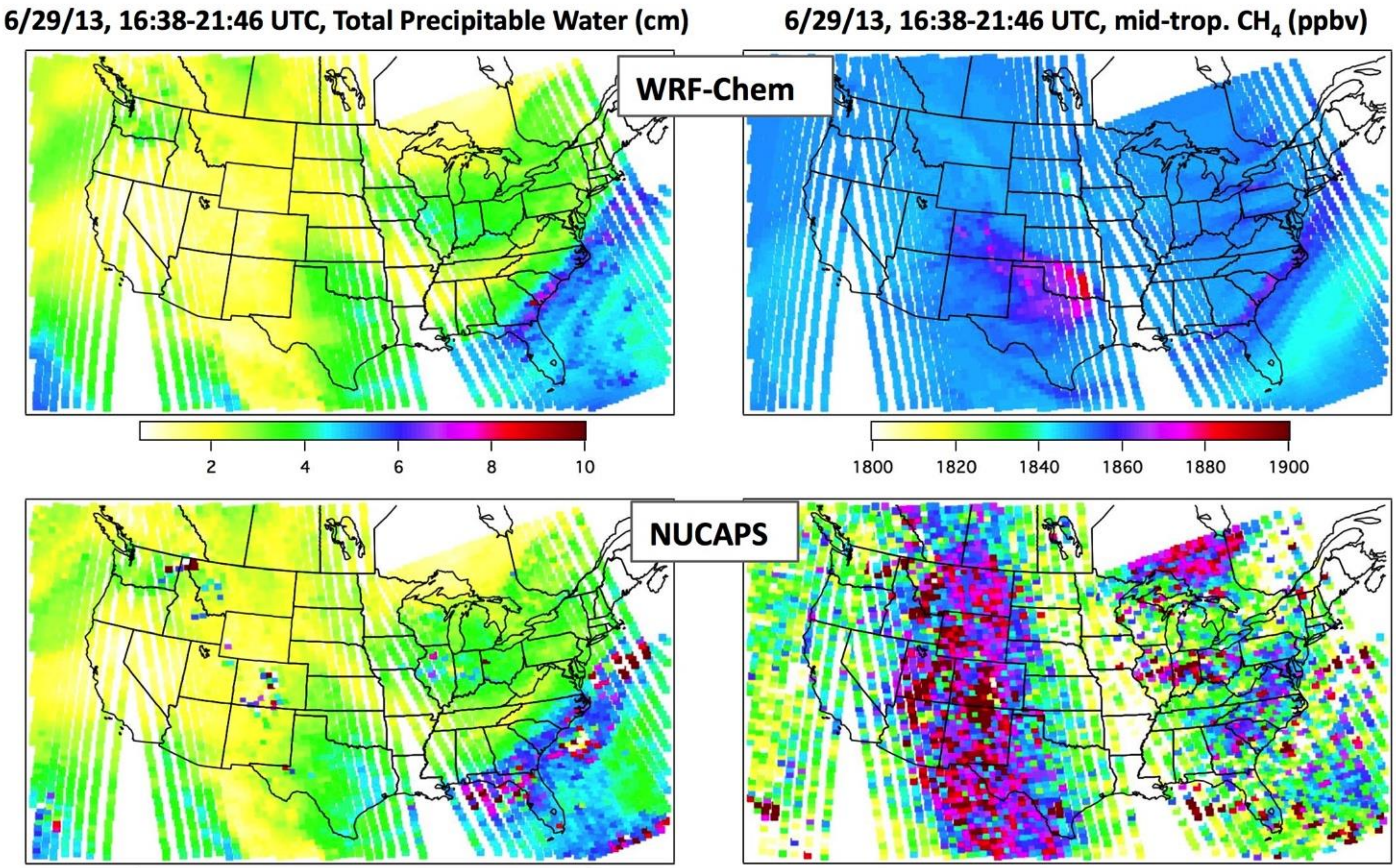




NUCAPS mid-tropospheric CH_4, acceptable QC data only

Brad Pierce

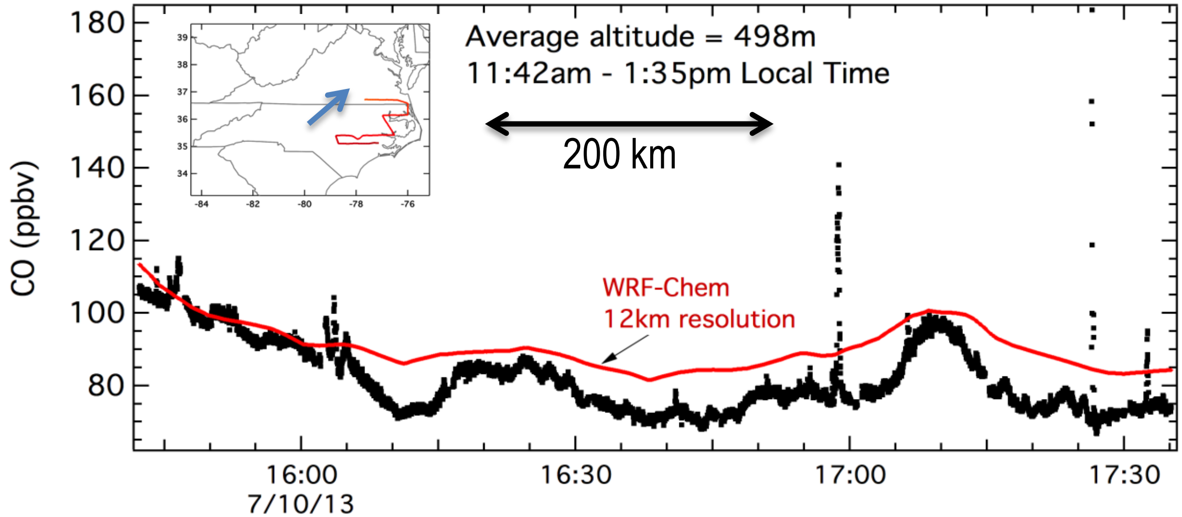
NUCAPS vs. WRF-Chem: CONUS



Brad Pierce, Stuart McKeen

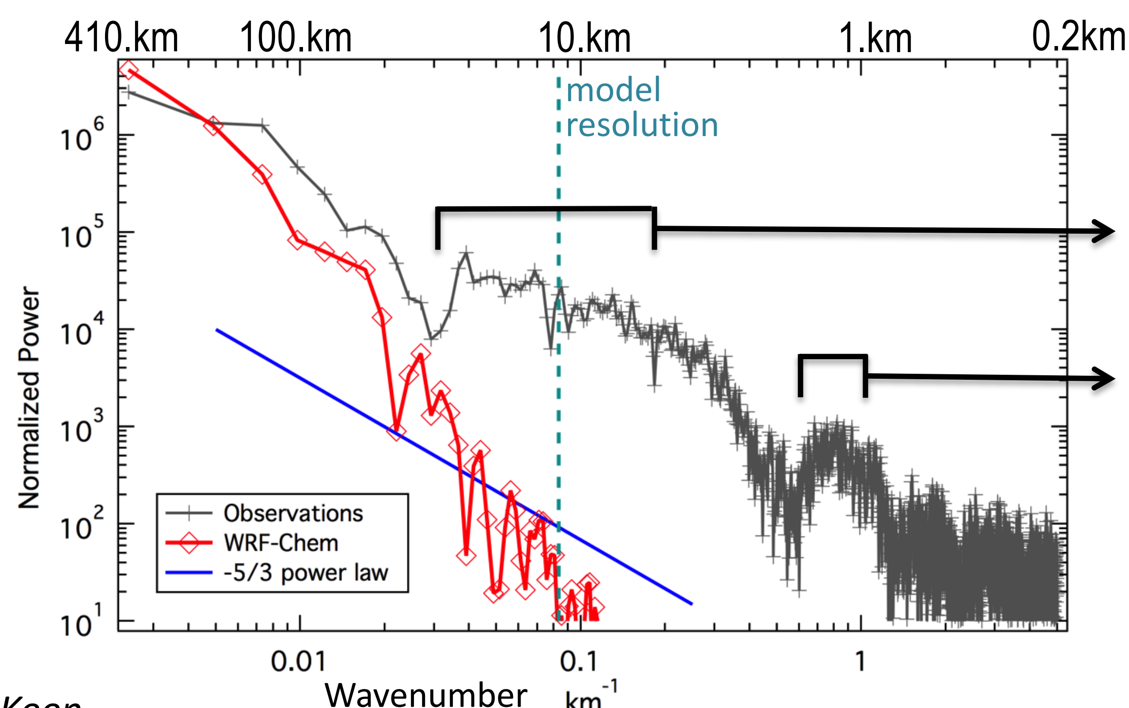
Analyzing the Scale Dependence of Variance – Fourier Transform Power Spectra

Example for Boundary Layer CO during SENEX-2013, one horizontal transect



<u>Urban Plumes:</u>
15:50 Raleigh/Durham
16:20 Greenville
17:10 Fayetteville

<u>Burning Plumes:</u>
Throughout transect



Length Scale

<u>5–30 km scale:</u>
combustion source areas (cities and towns)

<u>1-2km scale:</u>
Agricultural burn plumes

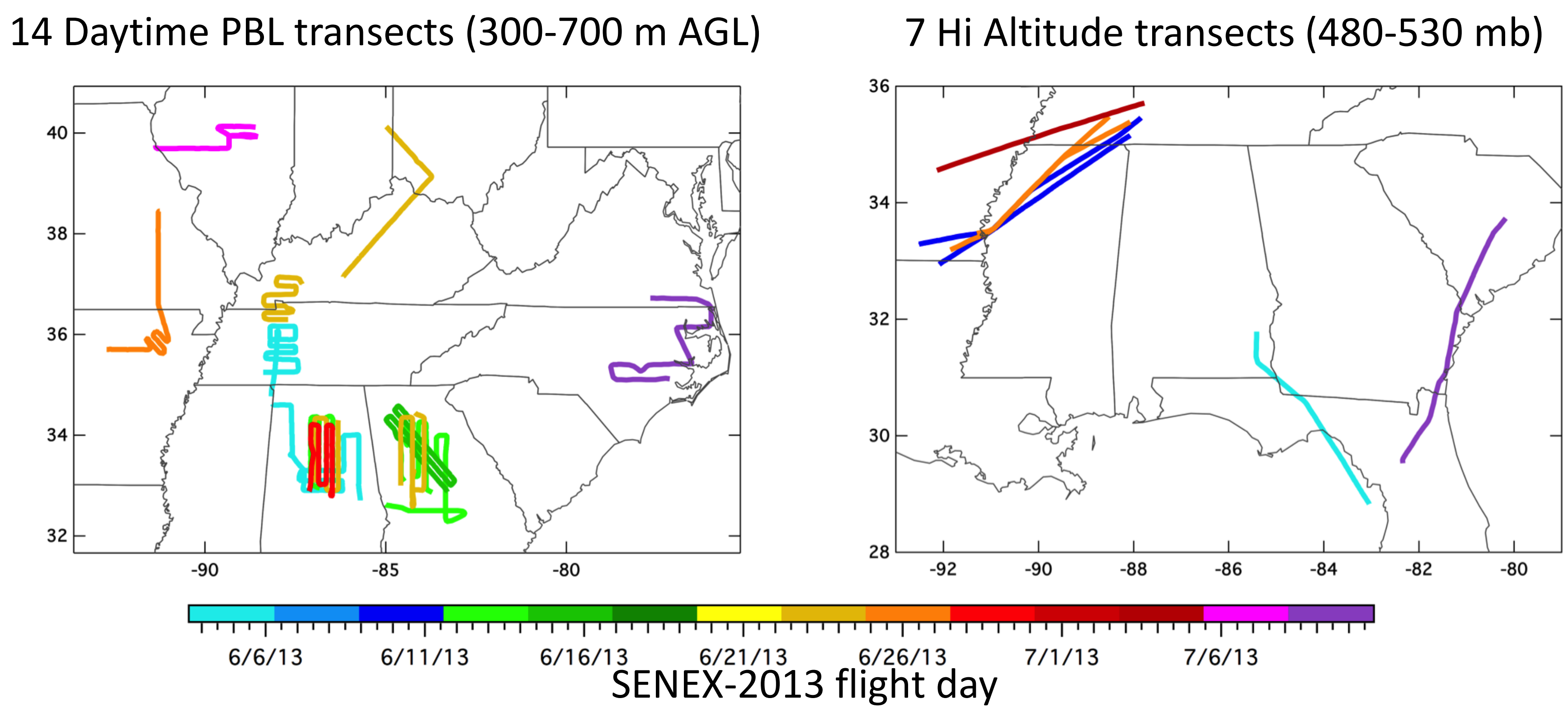
Power Spectra of CO depends on both emissions and transport

Model spectra somewhat similar to observations for length scales > 4ΔX

Stuart McKeen

Comparing Average Power Spectra for Water Vapor and CH_4,

within the boundary layer and at high altitude (~500mb)



14 transects, 10:00am-6:00pm EDT,
with N > 4096 for 1-Hz data

21.6 Hours of flight time

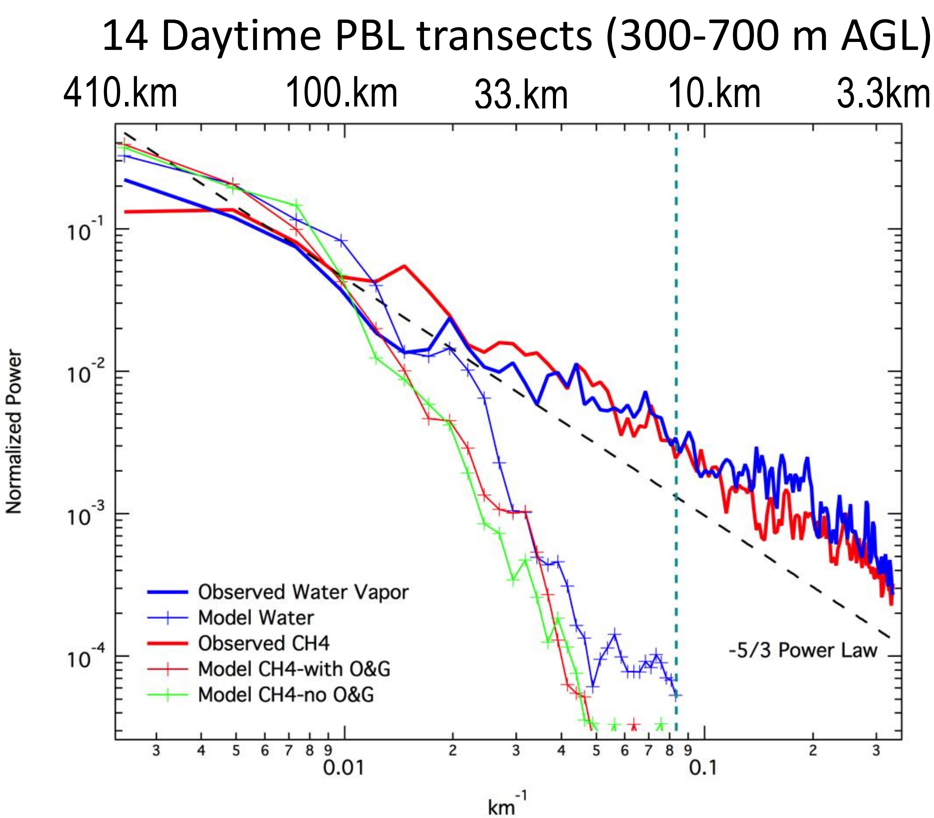
7 transects, day and night,
with N > 2048 for 1-Hz data

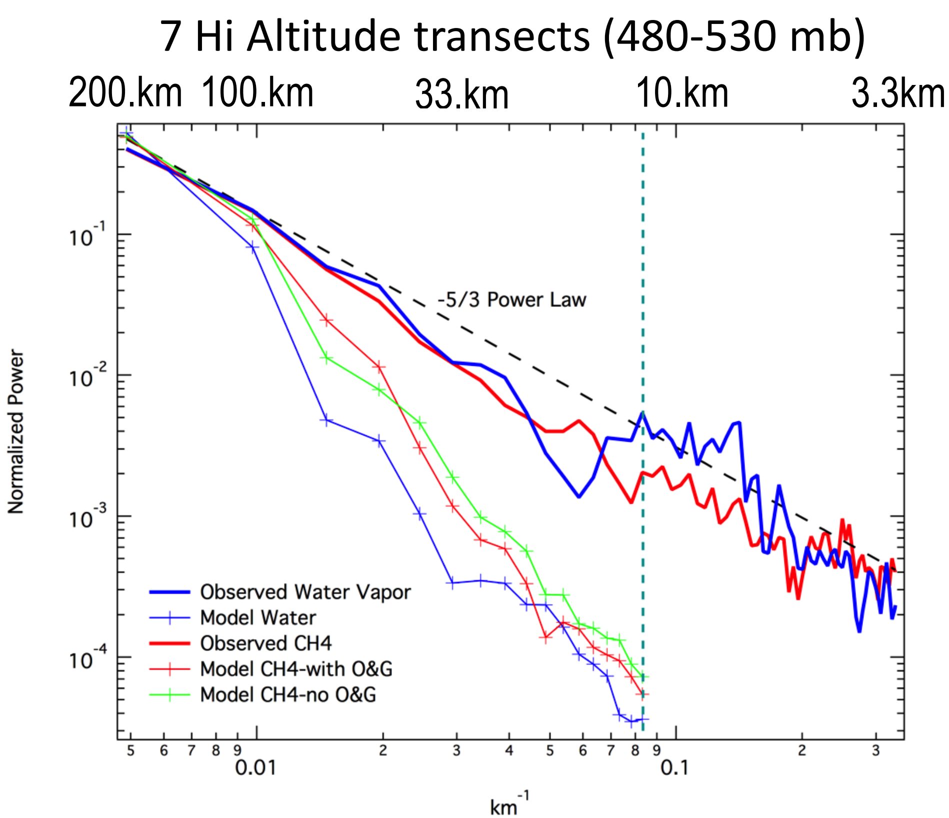
5.4 Hours of flight time

Stuart McKeen

Comparing Average Power Spectra for Water Vapor and CH_4,

within the boundary layer and at high altitude (~500mb)





Power spectra for CH_4 and H_2O show similar slopes and tendencies.
At high altitude the slope is about -5/3 for longer (>50 km) length scales.

Model H_2O vapor captures variability for length scales > 3ΔX in the PBL, > 7ΔX at 500mb.

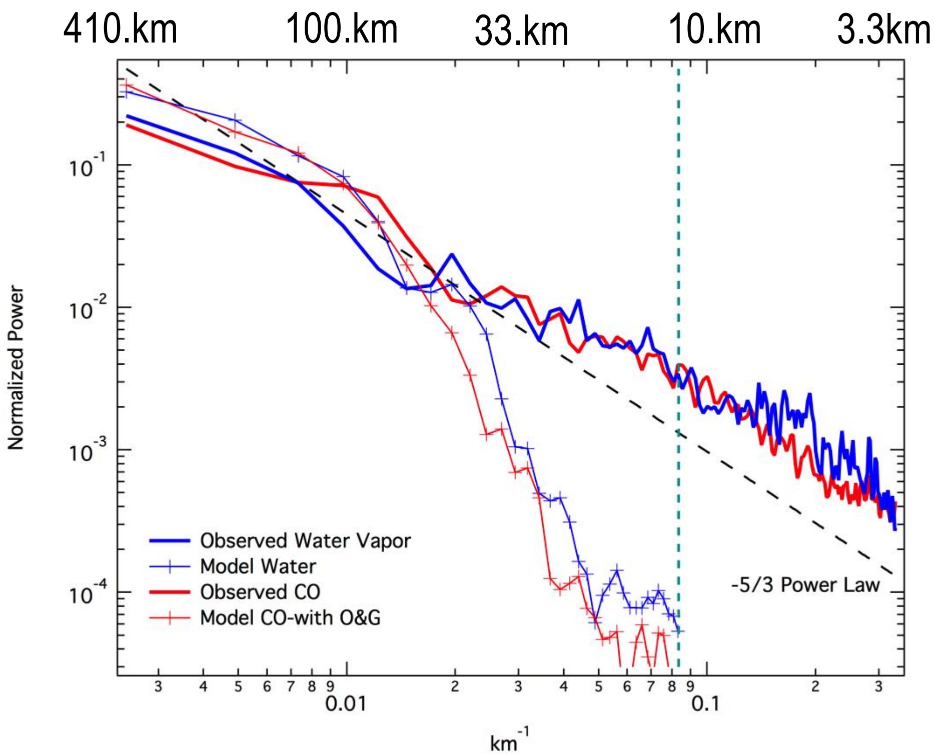
Adding/Removing model Oil/Gas emissions impacts CH_4 power spectra for both the PBL and high altitude transects.

Stuart McKeen

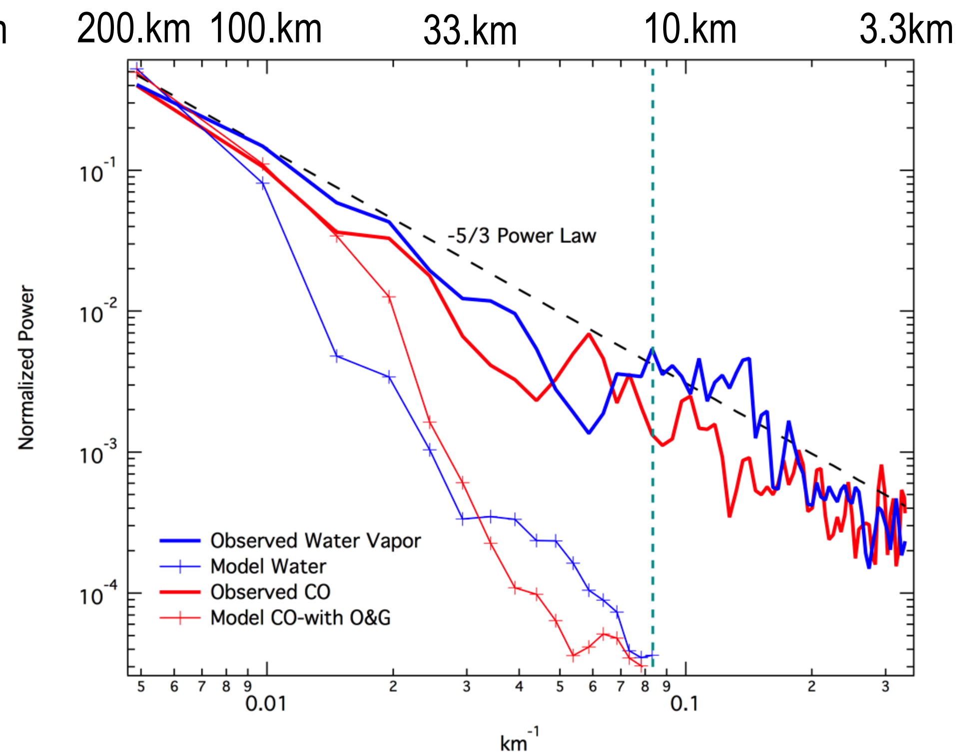
Comparing Average Power Spectra for Water Vapor and CO,

within the boundary layer and at high altitude (~500mb)

14 Daytime PBL transects (300-700 m AGL)



7 Hi Altitude transects (480-530 mb)



Power spectra for CO and H_2O show similar slopes and tendencies.
At high altitude the slope is about -5/3 for longer (>50 km) length scales.

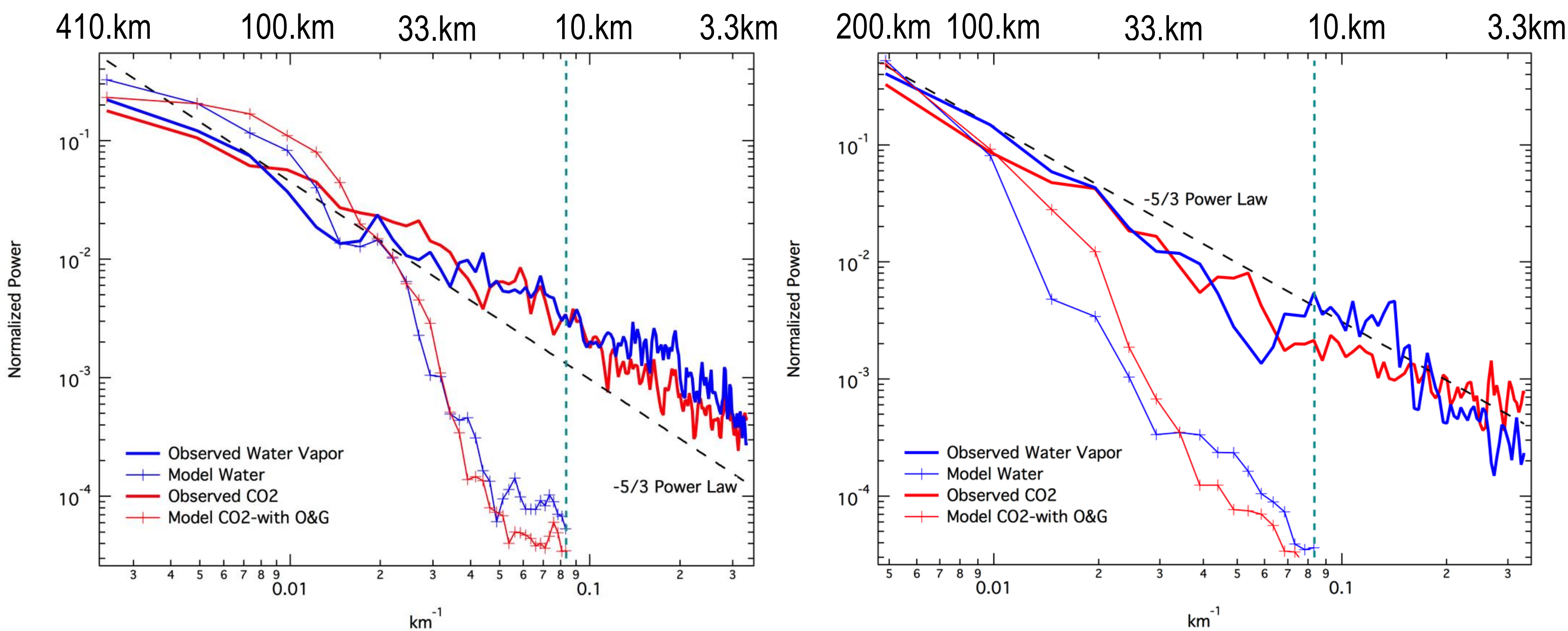
At high altitude model CO spectra more consistent than H_2O spectra
in the 40-50 km length scale range

Stuart McKeen

Comparing Average Power Spectra for Water Vapor and CO_2,

within the boundary layer and at high altitude (~500mb)

14 Daytime PBL transects (300-700 m AGL) | 7 Hi Altitude transects (480-530 mb)



Power spectra for CO_2 and H_2O show similar slopes and tendencies.
At high altitude the slope is about -5/3 for longer (>50 km) length scales.

At high altitude model CO_2 spectra more consistent than H_2O spectra in the 40-50 km length scale range

In the PBL, model CO_2 spectra flattens out at longer length scales. Note, the model does not include vegetative respiration, only anthropogenic sources.

Stuart McKeen

Aliso Canyon Gas Leak

http://www.latimes.com/local/california/la-me-aliso-well-hole-20160115-story.html

http://www.latimes.com/local/lanow/la-me-porter-ranch-gas-leak-live-htmlstory.html

Rapid incident response using airborne chemical measurements

Demonstrated right now in the Aliso Canyon well blowout in the Los Angeles Basin

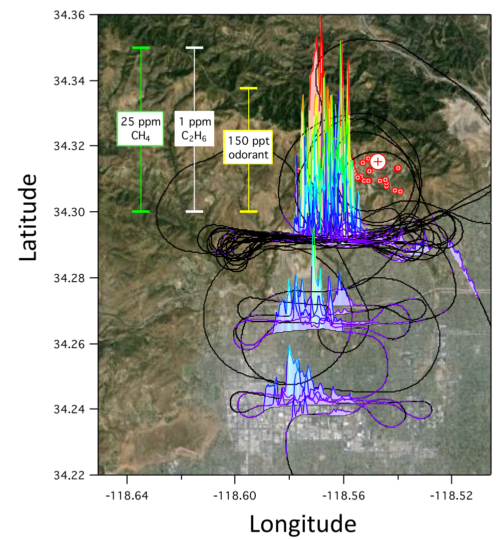
• A 61-year-old natural gas storage well in the densely populated San Fernando Valley near Los Angeles, CA blew out on 23 Oct 2015

• Ongoing gas leak has led to evacuation of thousands of homes, many hospitalizations, and a dozen lawsuits to date; a state of emergency was declared by Gov. Brown on 6 Jan 2016

• 6 research flights to date have provided the **only accurate assessment of methane leak rate,** its evolution over time, and climate and air quality consequences of this massive leak ***(data analysis and paper draft by NOAA CSD)***

communicated to CARB, SoCalGas, and the public immediately after each flight

One point source has effectively doubled the methane emissions rate of the entire LA Basin



Scientific Aviation Mooney TLS aircraft

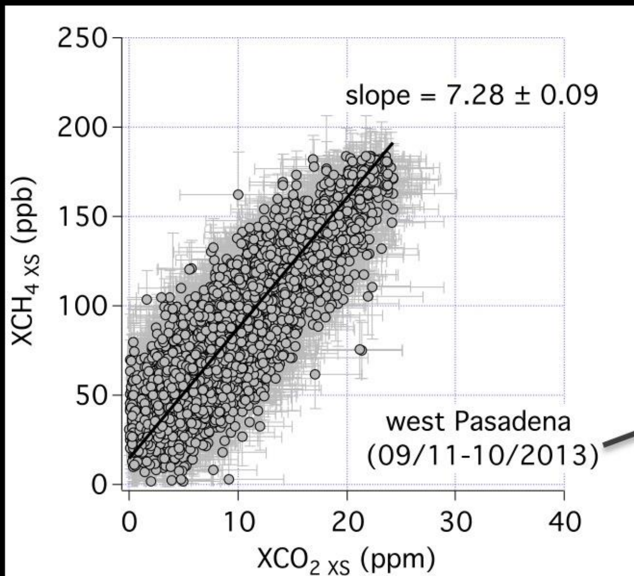
The airborne chemical response delivers:

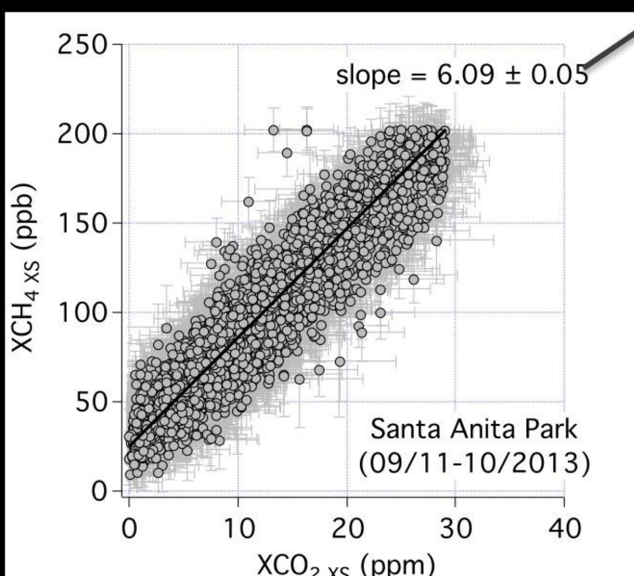
• time-critical and actionable information.
• benchmark for assessing scale of GHG mitigation actions as agreed by SoCalGas.

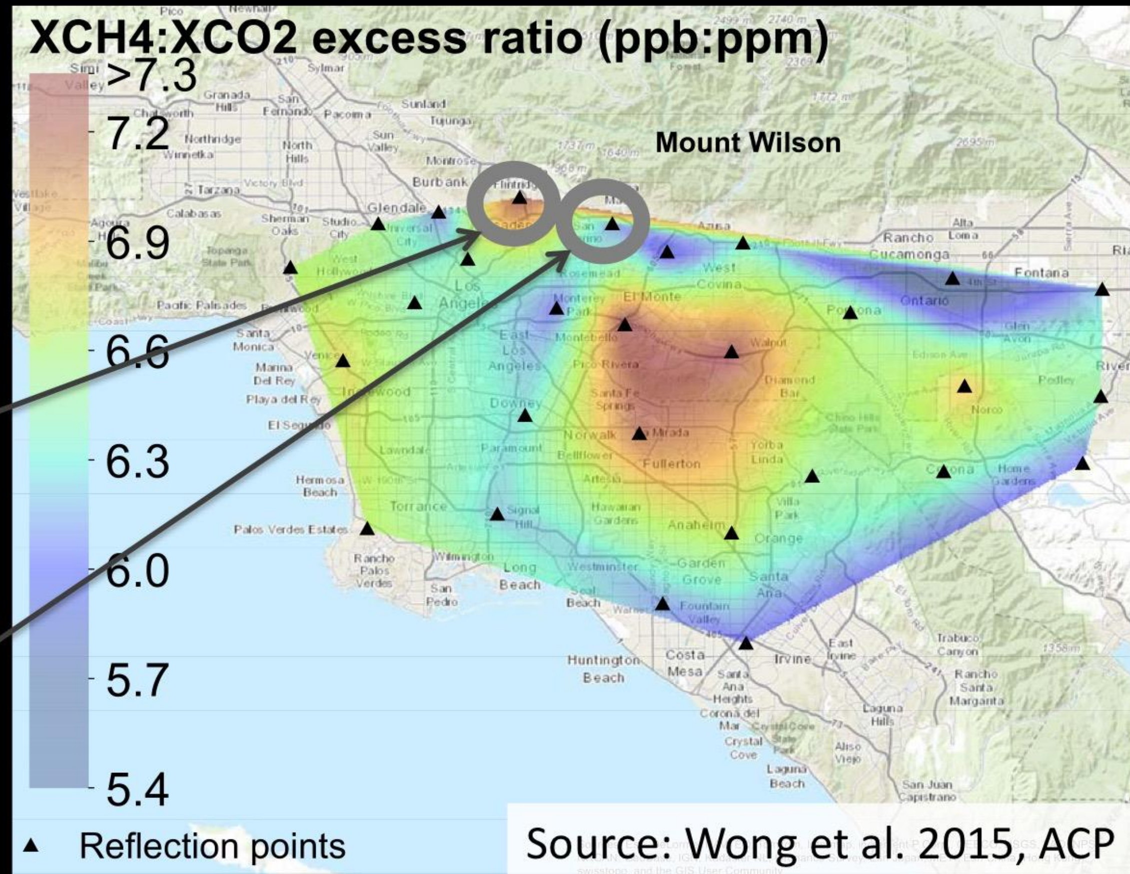
Tom Ryerson et al.

Correlations between $XCH_{4(xs)}$ and $XCO_{2(xs)}$

Stan Sander, Clare Wong, Thomas Pongetti, and the Megacities Carbon Project







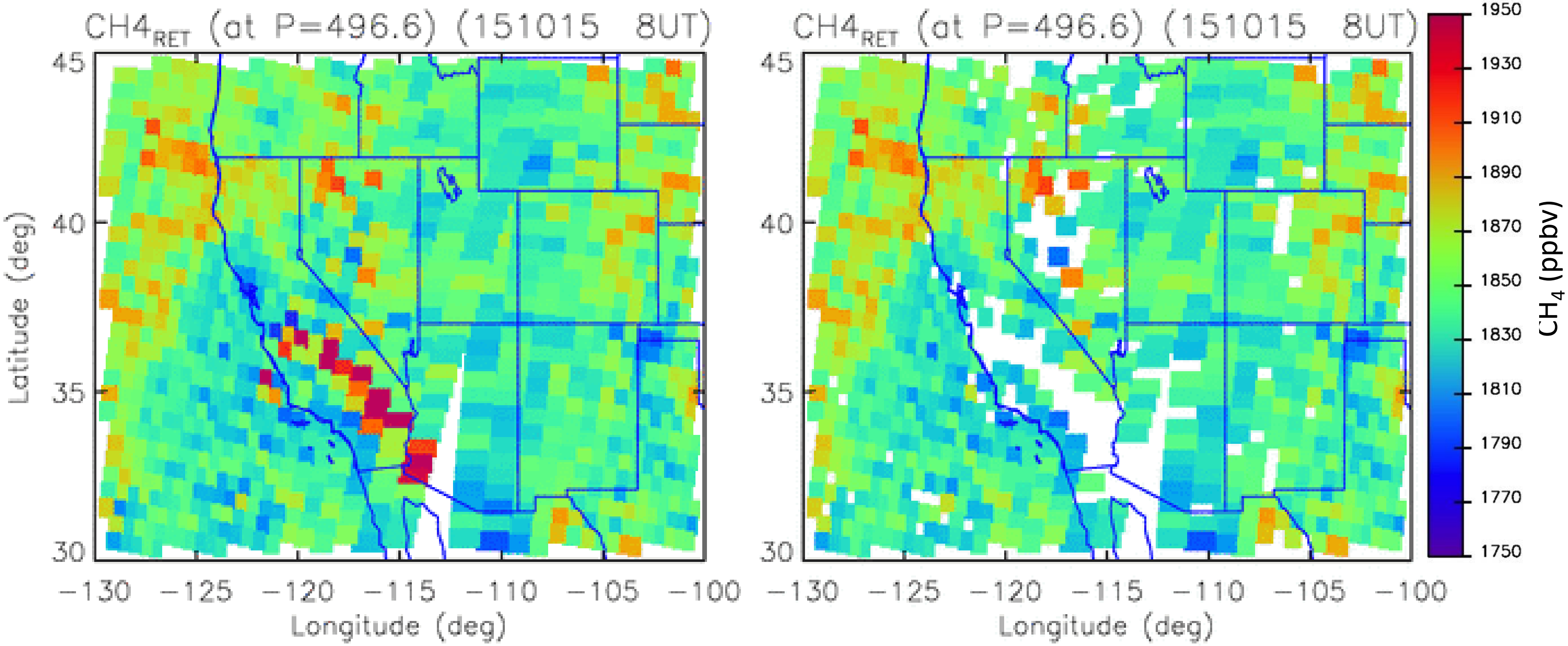
- XCH_4/XCO_2 is a more robust quantity that XCH_4 alone:
  - CH_4 emissions may be estimated using the ratio method since CO_2 emissions are relatively well known
  - Bias and systematic error from aerosol scattering cancel to first order CH_4 and CO_2 spectral bands lie nearby in frequency (Zhang et al. JGR, 2015)

NUCAPS CH_4, 15 Oct 2015 – 30 Nov 2016

497 mbar CH_4 from NUCAPS science retrievals
Both ascending (AM) and descending (PM) orbits shown

All data

"Acceptable" QC only



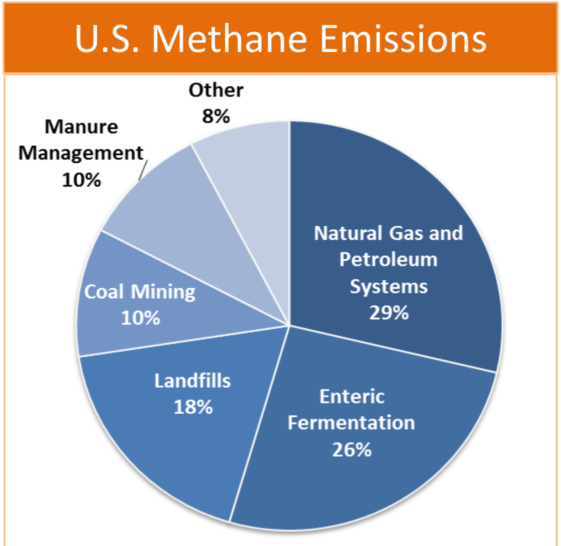
Chris Barnet

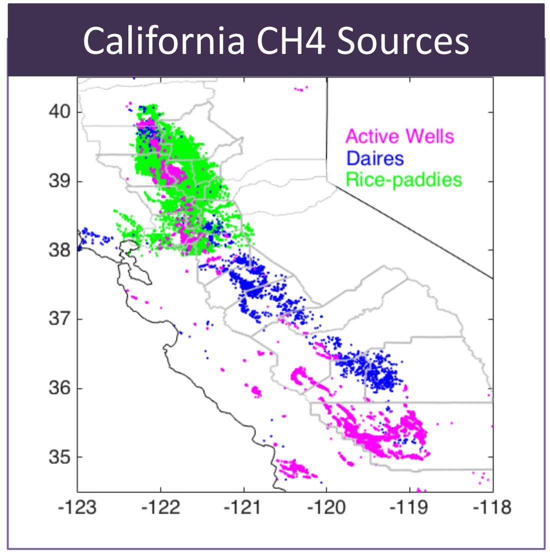
NUCAPS CH_4 Science Retrievals: Some Data Processing Issues

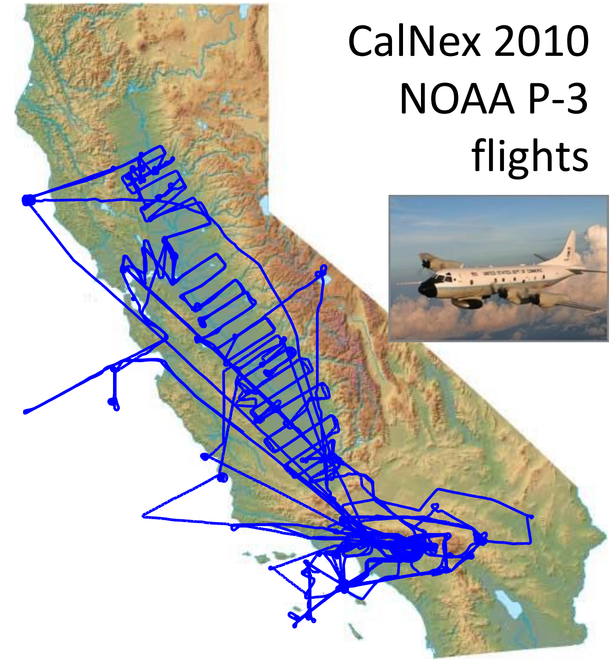
- Many granules not processed due to failures in pre-processor code, possibly from too stringent ATMS QC threshold
- "Acceptable" QC (QC = 0): Daytime data rejection >> nighttime over land, likely from too stringent CrIS QC threshold
- Very noisy CH_4 signal. Noise filter or averaging may be needed.

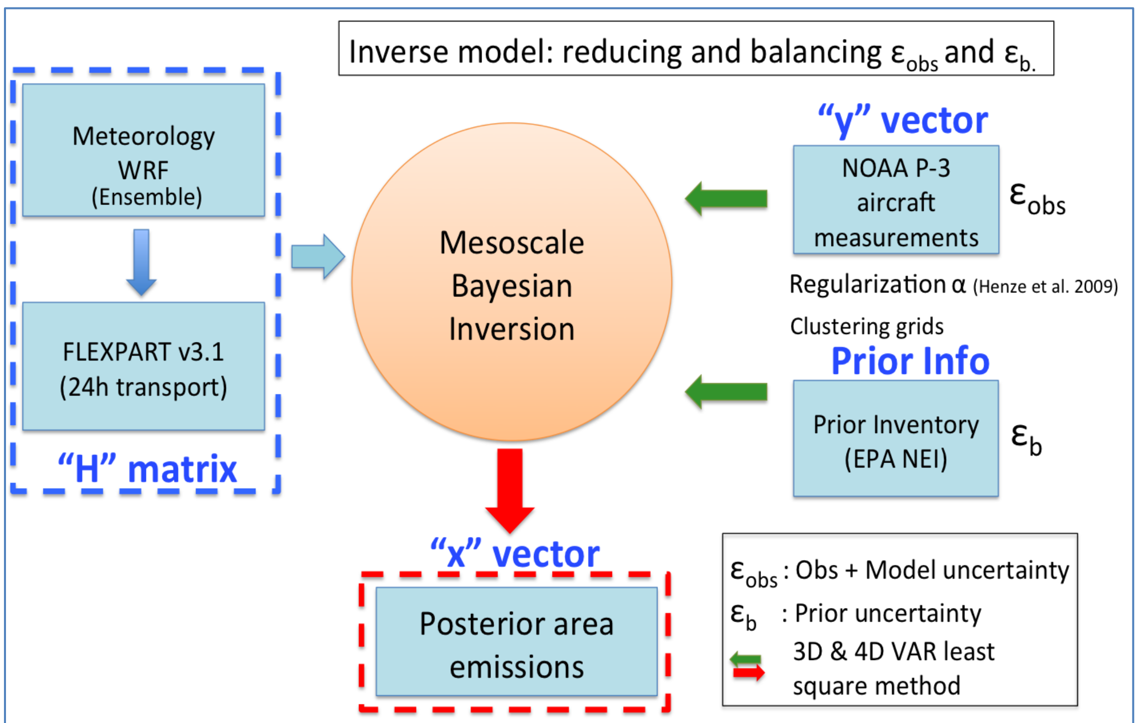
Chris Barnet

Inverse modeling to constrain CA CH_4 emissions





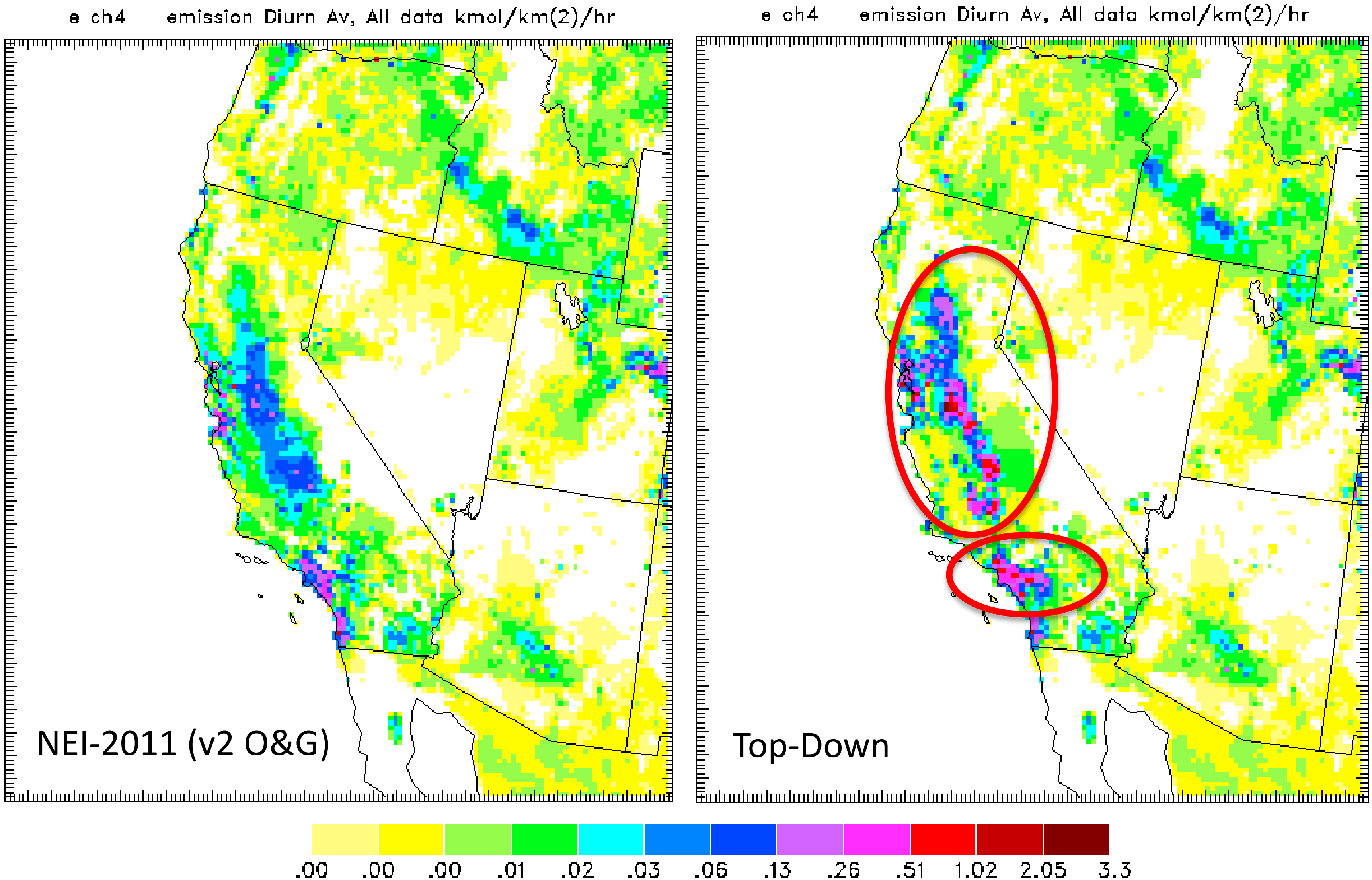




Mesoscale inverse modeling system

Y. Cui et al., JGR, 2015 & JGR, 2016

CH_4 Emissions Improvements from Inverse Modeling



Based on Y. Cui et al., JGR, 2015 & JGR, 2016

Future Work and Milestones

- Address NUCAPS CH_4 retrieval processing issues
- NUCAPS CH_4 analysis for SENEX 2013 period
- NUCAPS CH_4, CO analysis for SONGNEX 2015 period
- NUCAPS CH_4, CO analysis for Aliso Canyon gas leak
- Major Milestones and Completion Dates
  - NUCAPS evaluation for SENEX 2013 (Sept 2016)
  - NUCAPS evaluation for SONGNEX 2015 (Sept 2017)
  - NUCAPS evaluation for Aliso Canyon (?)
  - Overall JPSS constraints on US CH_4 and CO (June 2018)
  - Journal article & final project report submission (Sept 2018)